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EFFECTS OF ALTITUDE ON TURBOJET ENGINE PERFORMANCE

By William A. Fleming

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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EFFECTS OF ALTITUDE ON TURBOJET ENGINE PERFORMANCE

By William A. Fleming

SUMMARY

Component and over-all performance characteristics of several turbojet engines investigated at the NACA Lewis laboratory during the past several years are summarized in this report to indicate the effects of altitude on turbojet engine performance. Data presented herein were obtained over a range of altitude flight conditions in the altitude wind tunnel and an altitude chamber, and also over a range of inlet conditions in compressor component installations.

A summarization of data for several engines shows that failure of turbojet engine performance to generalize for all altitudes is primarily due to a decrease in compressor efficiency and corrected air flow with reduced Reynolds number index and a reduction in combustion efficiency with increased altitude. Data also show that, although engines of different design may have equal thrusts at sea level, the thrust can differ by as much as 26 percent at an altitude of 45,000 feet. These differences, which are introduced as a corrected engine speed effect, are primarily due to differences in compressor air flow and efficiency characteristics from one engine to another. The additional effects of Reynolds number on the performance variations with altitude from one engine to another are of much smaller magnitude than the corrected engine speed effect.

INTRODUCTION

The effect of altitude on turbojet engine performance can be approximated by the application of correction factors to the performance variables obtained at sea level. In the same manner, data obtained at several altitudes may be generalized or corrected to a reference altitude, usually sea level. Performance variables thus treated are referred to as "corrected" or "generalized" performance, examples of which are corrected engine speed $N/\sqrt{\theta}$ and corrected net thrust F_n/δ . The purpose of the factor δ is to correct for the effect of ambient pressure on the density of the engine air, and the purpose of the factor θ is to correct for the effect of temperature on the Mach numbers throughout the engine for each rotor speed. Definitions of the factors δ and θ , together with a complete list of corrected performance variables, are

given in the appendix. One derivation of these corrected performance variables which utilizes the concept of flow similarity is presented in reference 1.

In order to indicate deviations in performance variations with altitude among a number of turbojet engines and the causes of these deviations, thereby to provide a better understanding of the effect of altitude on turbojet engine performance, data obtained from investigations of several axial- and centrifugal-flow engines at the NACA Lewis laboratory during the last several years are summarized in this report. Discrepancies between actual engine performance at altitude and altitude performance predicted from sea-level data are critically examined for the various engines and the reasons for these discrepancies are traced to particular engine components. In addition, the pronounced effect of differences in compressor characteristics from one engine to another on the rate of thrust decay or variation of maximum corrected engine thrust with altitude is also examined. Data thus presented herein include component and over-all engine performance obtained in the altitude wind tunnel and an altitude test chamber, and compressor performance obtained in compressor installations.

APPARATUS

Altitude wind tunnel. - The altitude wind tunnel in which some of the engines were investigated is a closed-circuit return-type tunnel circular in cross section with a test section 20 feet in diameter and 40 feet long. Auxiliary tunnel equipment, including exhausters, refrigeration system, and drive motor and fan, are used to simulate altitude flight conditions. Engines being investigated are generally mounted in a fuselage or nacelle (fig. 1), which is connected to a six-component scale system by means of trunnions at either side of the test section.

Because it is desirable to simulate flight Mach numbers greater than those obtainable with the tunnel fan, dry refrigerated air from the tunnel make-up air system is introduced through a duct to the engine inlet. This air is throttled from approximately sea-level pressure to the desired total pressure at the engine inlet while the static pressure in the test section of the tunnel is maintained at the desired altitude condition. With this operating technique, the test-section pressure can be reduced to correspond to altitudes as high as 50,000 feet while the simulated flight Mach number is varied from zero to approximately 1.0. By the use of either electric heaters or refrigeration coils installed in the make-up air system, the engine-inlet temperature can be varied from 150° to -30° F.

Altitude chamber. - The altitude chamber in which some of the engines were investigated is 10 feet in diameter and 60 feet long. For centrifugal-flow-engine installations, the chamber is divided into two

sections, an inlet section and an exhaust section, separated by a steel bulkhead located at the rear of the engine. For axial-flow-engine installations, an additional bulkhead is installed at the engine inlet, which isolates the engine section from the inlet section (fig. 2). With this type of installation, small amounts of air are bled through a valve in the forward bulkhead and exhausted through an opening in the rear bulkhead to provide circulation in the engine section. The engines are mounted on the trunnions of a thrust-measuring bed with the tail pipe of the engines extending through the rear bulkhead into the exhaust section. Freedom of movement for the engine at the bulkheads is provided in both axial and radial directions.

Air at ram pressure is supplied to the inlet section of the chamber through a supply line from the laboratory air system. The temperature of this air can be varied from 85° to -50° F. In order to insure a uniform velocity profile at the engine inlet, the air is passed through a set of honeycomb vanes installed in the upstream end of the chamber. The hot gases discharged from the engine are removed from the exhaust section of the altitude chamber through a diffusing elbow and passed through two dry-type coolers before entering the laboratory exhaust system. The pressure in the exhaust section can be reduced to correspond to altitudes as high as 65,000 feet.

Compressor component installations. - In the compressor component installations the compressor, which was driven by a variable-frequency induction motor through a gear box, was mounted downstream of a stagnation chamber (fig. 3). Screens were fitted into the tank near the midsection to remove any foreign particles and to insure smooth flow. The inlet air passed through a submerged adjustable orifice in the inlet ducting, into the stagnation chamber, and then into the compressor. The air leaving the compressor passed through a collecting chamber and into the laboratory exhaust system. Compressor-inlet and -outlet pressures were regulated by butterfly throttle valves.

Inlet temperature and inlet pressure can be varied over the same range as in the altitude chamber. The inlet ducting, stagnation chamber, and the compressor were insulated to minimize heat transfer between the working fluid and room air.

Engines and compressors. - Data obtained with seven engines and two compressors are included in this report. The engines were designated as A to G; engines A to D were axial-flow engines and engines E to G were centrifugal-flow engines. The two compressors operated in compressor component installations were similar to those for engines C and F and are designated as such, but were in stages of development different from the ones used in the engines for the complete engine evaluations. Compressor C had only 10 stages, whereas the compressor in engine C had 11 stages. Characteristics of the engine components are summarized in the following table:

Engine	Compressor	Combustor	Turbine	Air flow at rated sea-level conditions (lb/sec)	Compressor pressure ratio at rated sea-level conditions
A	12-stage axial	8 tubular type through flow	Single stage	94	5.1
B	11-stage axial	8 tubular type through flow	Single stage	85	4.8
C	11-stage axial	double annular type through flow	Two-stage	58	3.8
D	11-stage axial	8 tubular type through flow	Single stage	73	4.0
E	double entry centrifugal	14 tubular type through flow	Single stage	78	4.0
F	double entry centrifugal	14 tubular type through flow	Single stage	90	4.6
G	single entry centrifugal	9 tubular type through flow	Single stage	91	4.4

INSTRUMENTATION

For the full-scale engine investigations, total and static pressures and indicated temperature were measured at the inlet and outlet of each component, except at the turbine inlet, where generally only the total pressure was measured. Sketches of survey rakes typical of those installed at several circumferential positions at each station in the engines are shown in figure 4. Engine air flow was determined from the compressor-inlet instrumentation on the axial-flow engines and with the tail-pipe-outlet instrumentation on the centrifugal-flow engines.

For the compressor component installations, pressure and temperature were measured in the stagnation chamber to determine the state of the inlet air. Compressor-outlet measurements were made with instrumentation similar to that used in the full-scale engines. Compressor air flow was measured by a submerged adjustable orifice located in a straight section of the inlet ducting upstream of the stagnation chamber.

PROCEDURE

When the engine performance data were being obtained, the engine-inlet total pressure and temperature and the exhaust-section or tunnel-test-section static pressure were set to correspond to the desired flight conditions for an NACA standard atmosphere, assuming complete free-stream ram pressure recovery at the engine inlet. The engine speed was then varied from the minimum to maximum value and both over-all and component performance data were obtained simultaneously. At each rotor speed investigated in the compressor component installation, the inlet-air temperature and pressure were maintained constant and the air flow was varied from the maximum obtainable with the laboratory air system to the point just preceding surge. Surging was detected audibly and by observing fluctuations on the pressure measuring manometers.

Methods of calculating each of the performance variables presented herein are discussed in the appendix.

RESULTS AND DISCUSSION

Effects of Altitude on Generalized Performance

When turbojet engine performance obtained at several altitudes was generalized to standard sea-level conditions by use of the correction factors δ and θ , it has been found that data obtained at high altitudes often deviate from those obtained at lower altitudes. An example of the types of deviations encountered with generalized engine performance is shown in figures 5 to 8, where performance data obtained at several altitudes with an axial- and a centrifugal-flow engine, engines B and F, respectively, (references 2 and 3) are corrected to standard sea-level conditions. These data, which are typical of most current axial- and centrifugal-flow engine performance, show that application of the temperature and pressure correction factors θ and δ failed to generalize each variable to a single curve. As indicated in these figures, the effects of altitude on the performance variables often became apparent only above altitudes of 30,000 to 40,000 feet. It is these secondary effects at high altitudes which will be of primary concern in the succeeding discussion.

With respect to the effects of altitude variations at a given corrected engine speed, an increase in altitude raised the corrected net thrust of the axial-flow engine and reduced the corrected thrust of the centrifugal-flow engine (fig. 5). For the other performance variables presented, an increase in altitude resulted in a decrease in corrected air flow (fig. 6), an increase in corrected specific fuel consumption (fig. 7), and an increase in corrected turbine-outlet temperature (fig. 8) for both engines. For a full understanding of the basic causes of these

altitude effects, it becomes necessary to trace the effects to their origin by examining the altitude performance of each engine component.

Effect of Inlet Conditions on Component Performance

Generalized data are presented showing the performance of each component over a range of inlet conditions in order to isolate the components affected by altitude. For each component, data for a number of engines were selected to show that the trends are typical of current engines.

Compressor. - The typical effect of altitude on compressor performance characteristics is illustrated in figure 9, in which performance maps are presented at two different compressor-inlet total pressures for the axial and centrifugal compressors of engines C and F operated in compressor component installations. The effect of inlet pressure on the variation of compressor pressure ratio with corrected air flow is shown for both compressors at three corrected compressor speeds with constant-efficiency contours superimposed. The reduction in inlet pressure shifted the constant compressor speed lines and efficiency contours as shown in the figure. Unpublished data further indicate that the peak efficiency of these compressors decreased as inlet pressure was reduced.

In order to indicate further effects of inlet pressure and to show the effect of inlet temperature, variations of compressor efficiency and corrected air flow with inlet total pressure are shown in figure 10 for engine A (reference 4) at a constant corrected compressor speed, pressure ratio, and two inlet total temperatures. Lowering either the inlet pressure or raising the inlet temperature resulted in reductions in both efficiency and corrected air flow.

It has been found that these effects of altitude or inlet pressure and temperature on compressor performance can be traced to an effect of Reynolds number on flow through compressors, as discussed in reference 4. These effects on performance are introduced by the shift in flow transition region on compressor blades with variation in Reynolds number in a similar manner to the well established shift in flow transition region on isolated airfoils. The effect of this shift in flow transition region with reduced Reynolds number was to reduce the air flow handling capacity and efficiency at a given corrected speed and pressure ratio in the manner illustrated in figures 9 and 10 for reductions in inlet pressure and increases in inlet temperature.

The association of Reynolds number with these effects is further illustrated by a correlation of the compressor performance of engine A with Reynolds number index, as shown in figure 11 for three corrected compressor speeds. For convenience, the parameter Reynolds number index

is used in place of Reynolds number because of the difficulty in selecting corresponding dimensions on which to base Reynolds number for use in comparing axial- and centrifugal-flow compressors. The relation between Reynolds number index and Reynolds number, as developed in reference 5, is included in the appendix. Data for each speed were obtained at two widely different values of inlet temperature; inlet pressures were selected for each temperature such that Reynolds number index remained constant. Although the independent variations of inlet temperature and pressure shown in figure 10 had a marked effect on performance, selecting the combination of inlet pressure and temperature so as to maintain Reynolds number index constant resulted in satisfactory correlation of the data. This correlation is typical of that illustrated by additional data included in reference 4 for a wide range of inlet pressures.

Variation of corrected air flow and efficiency with Reynolds number index is shown in figure 12 for five compressors (A, reference 6; C, reference 7; D, reference 8; E, reference 9; and F) operating at rated corrected compressor speed and constant pressure ratio. The decrease in corrected air flow and efficiency was evident for each compressor, although the effect was more pronounced with some compressors than with others. Such a pronounced Reynolds number effect on the performance of current turbojet compressors is an important factor contributing to the secondary effects of altitude on over-all engine performance. This relation will be discussed more fully in a later section.

Turbines. - Any altitude effects on turbine performance might also be expected to originate from variations in Reynolds number. Because the pressure and temperature, and consequently Reynolds number index, at the inlet of a turbine installed in an engine vary with engine speed at a given flight condition, it becomes most expedient to compare the data on the basis of engine-inlet total pressure rather than turbine Reynolds number index.

The effect of engine-inlet total pressure on the performance of the turbines in four engines (A, reference 10; B; D, reference 11; and F) is shown in figures 13 and 14. In no case was there any effect of inlet pressure on the corrected turbine gas flow. Turbine efficiencies were also unaffected except that with very low engine-inlet pressures, 181 and 262 pounds per square foot, the efficiencies of turbines B and F were reduced by $1\frac{1}{2}$ to 3 percent. At these very low inlet pressures, which correspond to turbine Reynolds number indices in the region of 0.08 to 0.13, Reynolds number effects are becoming apparent in the turbine. Because these effects were apparent only at engine-inlet pressures which would be encountered at altitudes above about 50,000 feet, the performance of current engines operating up to this altitude should be essentially unaffected by Reynolds number effects on turbine performance.

Combustor. - Because the exact mechanism of combustion in a turbojet combustor is not yet fully understood, no technique for generalizing combustor performance is universally accepted. Attempts have been made to generalize the data by plotting combustor performance, that is combustion efficiency η_b and total-pressure-loss ratio $\frac{P_2 - P_3}{P_2}$, as functions of corrected engine speed $N/\sqrt{\theta_2}$, as in reference 12. One experimenter (reference 13) developed a correlation of combustor performance in which combustion efficiency was a function only of $\frac{P_2 T_2}{V_2}$. Others working with combustor performance have employed still different techniques which were basically similar to these. Thus far, however, no technique has been found which will satisfactorily generalize the combustor performance of a large number of different engines.

Because no satisfactory generalizing techniques are known, the combustor data herein are presented to show the effect of altitude or pressure on performance, with no attempt to generalize the data. Combustion efficiency and combustor total pressure loss ratio $\frac{P_2 - P_3}{P_2}$ are shown as functions of engine-inlet total pressure at three corrected engine speeds in figures 15 and 16, respectively, for four engines (A, reference 12; B; C, reference 14; and F). As engine-inlet pressure is varied at a constant corrected engine speed, the combustor-inlet corrected velocity $V_2/\sqrt{\theta}$ and corrected temperature T_2/θ remain essentially constant; any small variations have a decided secondary effect on combustor performance.

The variation of combustion efficiency with engine inlet total pressure (fig. 15) illustrates the characteristic decrease in efficiency with reductions in both engine inlet pressure and corrected engine speed. As shown, the effects of both pressure and corrected speed differ greatly from one engine to another; little effect on the combustion efficiency was noted in engine A as compared with the other engines. The decided reductions in efficiency at reduced corrected speeds and inlet pressures significantly increase the specific fuel consumption of engines at high altitudes. Also, the large differences in these effects from one engine to another account for similar differences in specific fuel consumption among engines at high altitudes, although the sea-level values may be the same.

There was little effect of inlet pressure on the combustor total-pressure-loss ratio (fig. 16). The total-pressure-loss ratio decreased slightly as inlet pressure was reduced, except for engine F, which exhibited the opposite trend. These trends, which in each case amounted to less than a 1-percent reduction in total pressure, are considered of

secondary importance, since a combustor total pressure loss of 1 percent will reduce the thrust and increase specific fuel consumption by about 1 percent. Reductions in corrected speed from the rated value to 80 percent of rated speed increased the total pressure loss by as much as 2 percent in some cases, although the pressure-loss ratio of engine B was reduced slightly. These trends with corrected engine speed similarly influence the variation of specific fuel consumption with corrected speed.

Exhaust system. - Changes in the swirl angle of the flow leaving the turbine with engine operating condition or changes in Reynolds number affecting the flow separation from the walls of the tail pipe can affect the total pressure losses through the exhaust system. Since these total pressure losses are reflected by reductions in jet thrust, the pressure loss across the exhaust system can be represented in terms of the ratio of measured to theoretical jet thrust, where the measured thrust is obtained from balance-system measurements and the theoretical thrust is based on the total pressure, total temperature, and gas flow entering the exhaust system. In order to indicate whether engine operating conditions or Reynolds number affected the flow through the exhaust system of the engine, the ratio of measured to theoretical jet thrust was plotted as a function of pressure ratio across the exhaust system for two engines (A and C) at several ambient pressures (fig. 17). These data cover a wide range of engine operating conditions, including variations in both altitude and engine speed. Although the scatter of the data was fairly large, there were no evident trends of jet thrust ratio with ambient pressure; consequently, it is concluded that the flow through the exhaust system was unaffected by engine operating condition or Reynolds number.

Effect of Compressor and Combustor on

Generalized Engine Performance

The compressor and combustor were shown to be the only components which had significant performance variations over a wide range of altitudes. The manner in which these component performance variations are reflected in the over-all engine performance are next considered.

The shift in compressor operating point with altitude for a given compressor Mach number is developed in figures 18 and 19 for an axial- and a centrifugal-flow compressor (engines B and F, respectively). The shift in compressor corrected speed line with altitude, which was previously discussed, is shown in figures 18(a) and 19(a).

A compressor being run in an engine will operate at only one pressure ratio and air flow for any given speed and altitude; consequently, as the engine speed is varied the compressor operates along an operating

line which passes through the compressor-characteristic map. With an increase in altitude, the operating lines for both compressors shifted to higher pressure ratios at a given corrected air flow (figs. 18(b) and 19(b)). This upward shift in the operating lines results from the reduction in compressor efficiency at altitude; more power from the turbine per pound of air flow is then required to drive the compressor. The interaction of the compressor, turbine, and fixed-area exhaust nozzle resulting from this increased demand on the turbine requires that the compressor pressure ratio at any given corrected air flow be increased to maintain an equilibrium operating condition.

Superimposing the corrected compressor speed and operating lines for each compressor (figs. 18(c) and 19(c)) gave the operating points at sea level A and at an altitude of 50,000 feet B. The axial-flow compressor operated along the steep portion of the compressor corrected speed line. Consequently the upward shift of the operating line combined with the shift in the corrected speed line as the altitude was increased moved the compressor operating point to a higher pressure ratio and lower corrected air flow. The centrifugal-flow compressor, on the other hand, operated on the more nearly horizontal portion of the compressor corrected speed line. Because of this characteristic, the downward shift in the corrected speed line with increased altitude more than offset the upward shift in operating line with the result that both the air flow and pressure ratio at the operating point were reduced by an increase in altitude. These shifts in compressor operating point with an accompanying reduction in compressor efficiency at high altitude are reflected in the over-all engine performance.

The effects of these changes in compressor operating point, with attendant changes in turbine operating point, and the reductions in combustion efficiency at altitude on over-all performance of both an axial- and a centrifugal-flow engine are illustrated in figures 20 to 23. These figures present the primary performance variables of engines B and F as functions of Reynolds number index for constant corrected engine speeds and flight Mach numbers. The performance variables include the corrected jet thrust parameter, the corrected air flow, the corrected turbine-outlet total temperature, and corrected fuel flow. Each variable is presented as the ratio of the corrected altitude value to the value at sea level.

As altitude was increased and the Reynolds number index reduced, the corrected jet thrust parameter was increased for the axial-flow engine and, except at one condition, was reduced for the centrifugal-flow engine (fig. 20), although the corrected air flow (fig. 21) was reduced for both engines. The shift in operating point of the axial-flow compressor to a higher pressure ratio as shown in figure 18(c) and the reduction in efficiency were reflected in an increase in turbine-outlet total temperature at reduced Reynolds number indices (figs. 22(a) to 22(c)), which was

accompanied by an increase in turbine-outlet total pressure. These increases with altitude more than offset the reduced air flow with the resulting rise in corrected jet thrust parameter. The shift in operating point of the centrifugal-flow compressor to a lower pressure ratio (fig. 19(c)), in addition to the reduced efficiency (fig. 12), resulted in an increase in corrected turbine-outlet temperature only at very low Reynolds number indices for the two lower engine speeds (figs. 22(e) and 22(f)) and a decrease in turbine-outlet total pressure at each speed. The combined reduction in corrected air flow and turbine-outlet total pressure offset the rise in turbine-outlet temperature, which thereby accounts for the drop in corrected jet thrust parameter of this engine at high altitudes.

The decreases in both compressor and combustion efficiency resulted in the increase in corrected fuel flow at low Reynolds number indices for both engines (fig. 23). The majority of this increase in corrected fuel flow resulted from reduced combustion efficiency. Analysis of the data indicated that adjusting the fuel flows to unity combustion efficiency for all conditions greatly reduced the severity of the corrected fuel flow variation with Reynolds number index. In one case, rated speed with the centrifugal-flow engine, the corrected fuel flow adjusted to unity combustion efficiency actually decreased with decreasing Reynolds number index. This reduction resulted from the reduced corrected air flow and constant turbine-outlet temperature for that operating condition.

The variation of generalized performance with altitude or Reynolds number index for other current axial- and centrifugal-flow turbojet engines has been shown elsewhere (references 2, 3, and 15 to 18) to exhibit trends similar to those shown for engines B and F. Therefore, although the magnitude of the variations differ from one engine to another, and in one case between two engines of the same design (reference 3), the trends illustrated here are typical.

Comparison of Corrected Engine Speed and Reynolds Number

Effects on Altitude Performance

An effect of altitude which is generally overlooked in discussing performance of isolated turbojet engines is the difference in performance variations, primarily, corrected thrust, with corrected engine speed from one engine to another. Such differences in the slope of the corrected net thrust curve plotted against corrected engine speed is often of such magnitude to completely overshadow the Reynolds number effects.

These differences are illustrated by the variation of corrected net thrust with corrected engine speed, shown in figure 24 for centrifugal-flow engine F and axial-flow engine B, the two engines for which performance data were presented in figures 5 to 8. The corrected thrust is

presented as a fraction of sea-level thrust at rated speed and the corrected speed is presented as a fraction of rated speed. Consequently, the sea-level thrust ratio for both engines is unity at rated corrected engine speed. The corrected thrusts at sea level and at an altitude of 50,000 feet are shown for engines F and B at flight Mach numbers of 0.67 and 0.62, respectively. This small difference in flight Mach number has an insignificant effect on the slope of the curves. As altitude is increased with an attendant reduction in ambient air temperature, the corrected speed and corrected thrust increase, until at an altitude of 50,000 feet the corrected speed ratio is 1.14 when the engines are operating at rated speed. A predicted corrected thrust at rated speed and based on sea-level data is indicated at this operating point on the sea-level curve. Because of the Reynolds number effects previously discussed, the thrust curve for an altitude of 50,000 feet is displaced as shown and the actual thrust available occurred at slightly less than the rated speed condition for both engines, because of the turbine-temperature limitations.

It is apparent from these data that at an altitude of 50,000 feet both the actual and predicted corrected thrust of the centrifugal-flow engine reached a considerably higher percent of sea-level thrust than for the axial-flow engine. In the succeeding discussion, the magnitude of these differences in the ratio of corrected altitude thrust to sea-level thrust will be compared with the magnitude of the Reynolds number effect on maximum thrust at altitude.

Reynolds number effects. - The reduction in engine speed required as altitude was increased to avoid excessive turbine temperatures is shown in figure 25(a) for five engines (A, B, C, G, and F). In each case the temperature-limited speed was restricted below the rated speed as altitude was increased; the reduction was 1 to 10 percent for the five engines at an altitude of 45,000 feet. The attendant variation in maximum thrust with altitude compared with the value predicted from sea-level data is shown in figure 25(b). For each engine, except engine B, the maximum thrust fell below the predicted value and, at an altitude of 45,000 feet, varied from 1/2 percent above to as much as 14 percent below the predicted value. The opposite trend for engine B resulted from the upward shift in the corrected thrust curve with increased altitude shown in figure 24(b), which more than compensated for the effect of the reduction in maximum speed. Differences in magnitude of the trends among engines were dependent on the amount the air flow was affected by speed reductions and the manner in which the compressor operating point was shifted by the Reynolds number effects.

Variation of the ratio of actual to predicted specific fuel consumption with altitude is shown in figure 25(c) for the same conditions. Because of reductions in both compressor efficiency and combustion efficiency, the specific fuel consumption of each engine, except engine A, increased at high altitudes above the predicted value. With this exception, the specific fuel consumption at an altitude of 45,000 feet was

3 to 20 percent higher than the predicted values. The reduction in specific fuel consumption for engine A resulted primarily from the fact that the compressor operated at a considerably higher efficiency at the reduced speed at altitude than that predicted from sea-level data for rated speed operation.

It might be expected that use of a variable-area exhaust nozzle, which permits operation at rated speed and limiting turbine temperature at all altitudes, would reduce or eliminate this difference between actual and predicted thrust at altitude. In order to explore this possibility, variation with altitude of the ratio of maximum thrust with a variable-area nozzle to maximum obtainable thrust with a fixed-area nozzle is shown for the five engines in figure 26(a). Exhaust-nozzle velocity coefficients of the fixed- and variable-area nozzles were assumed equal. These data indicate little or no gain in maximum thrust at altitude by use of the variable-area nozzle, except for engine C, which gained 4 percent in thrust at an altitude of 45,000 feet. Analysis of the performance of this engine indicated that at a higher flight Mach number, comparable with that of the other engines, most of this gain would vanish. Comparison of the specific fuel consumptions in figure 26(b) shows that for all but one engine the specific fuel consumption at high altitudes was higher for rated speed operation at limiting temperature than at the temperature-limited speed with a fixed nozzle.

These trends can be explained by use of figure 27 which presents the variation of corrected air flow and compressor efficiency with corrected engine speed for each engine at high altitude. The temperature-limited speed of each engine is indicated on the figure by ticks on the curves and the common value of rated speed is indicated by the vertical line. Although the air flow for each engine rose slightly with the increase from temperature-limited speed to rated speed (fig. 25(a)), the compressor efficiency was reduced because the engines were operating on the negative slope of the compressor efficiency curves. The consequent reduction in compressor efficiency for operation in this region resulted in a decrease in total pressure ratio across the engine P_4/P_1 . In most cases, this decrease in engine pressure ratio nearly offset the increase in air flow thereby resulting in little or no increase in thrust and a rise in specific fuel consumption (fig. 26).

When the added weight, complication, and possible lower velocity coefficients of the variable-area nozzle as compared with those of a fixed-area nozzle are considered, there is no apparent advantage in using a variable-area nozzle to permit operation at rated engine speed at altitude. Actually, the variable-area nozzle would be detrimental in some cases, because of the rise in specific fuel consumption.

Corrected engine speed effects. - Consideration will next be given to the effect of corrected engine speed on the corrected performance at altitude and the magnitude of differences in this effect from one engine

to another as compared with the Reynolds number effects. In order to isolate the corrected speed effect, the variation with altitude of the ratio of maximum corrected net thrust predicted at altitude to sea-level thrust at rated speed is shown in figure 28(a). These data illustrate the increase of this corrected net thrust ratio with altitude as corrected engine speed was increased by the reduction in ambient air temperature. As shown, the thrust ratio for centrifugal-flow engines F and G increased to slightly over 1.70 above the tropopause as compared with approximately 1.35 for axial-flow engines A and B. In other words, on the basis of sea-level performance data, if the sea-level thrusts of these engines were equal, thrust of engines F and G above the tropopause would be approximately 26 percent higher than that of engines A and B. The data for engine C are not directly comparable with the other data because of the difference in flight Mach number. Examination of the performance data indicated that raising the flight Mach number from 0.25 to 0.60 would reduce the thrust ratio of this engine above the tropopause by approximately 5 percent because of differences in slope of the net thrust curves.

For each engine the ratio of predicted to sea-level specific fuel consumptions decreased up to the tropopause (fig. 28(b)), except for engine A, which suffered a severe reduction in compressor efficiency at high corrected engine speeds. In general, the reduction in specific fuel consumption was greater for the engines having the greatest rise in predicted to sea-level thrust ratio with an increase in altitude.

Combining the Reynolds number effect shown in figure 25(b) with the corrected speed effect (fig. 28(a)), to give the ratio of corrected maximum net thrust at altitude to sea-level net thrust at rated speed, results in the trends shown in figure 29(a). At an altitude of 45,000 feet the thrust ratios for the axial-flow engines fell between 1.23 to 1.34 as compared with 1.53 to 1.61 for the centrifugal-flow engines. Correspondingly, if all engines had the same thrust at sea level, the centrifugal-flow engines would give 14 to 31 percent more thrust at an altitude of 45,000 feet than the axial-flow engines.

The ratio of actual to sea-level specific fuel consumption remained essentially constant up to an altitude of about 30,000 feet for the axial-flow engines and decreased rather rapidly for the centrifugal-flow engines (fig. 29(b)). Above this altitude, the specific fuel consumption increased very markedly for the centrifugal-flow engines and more gradually for the axial-flow engines. This increase was mainly due to reduced compressor and combustor efficiencies.

The differences in the trends of the thrust ratio between the axial- and centrifugal-flow engines is not inherent in the respective compressor types, but is associated with the relative air flow per unit flow area of the compressors when they are operated at rated corrected speed and above.

2326 This comparison is illustrated by the corrected air flow and compressor efficiency shown for each of the five engines in figure 27. These data show that the corrected air flow for the centrifugal-flow engines continued to increase more rapidly than that for the axial-flow engines above rated corrected speed, which accounts for a small portion of the difference in the ratio of altitude to sea-level thrust. The difference in air flow characteristics results from the fact that the axial-flow compressors, particularly those of engines A and B, had a very high air flow per unit area and were near choking in the early stages at rated speed, whereas the compressors of engines F and G were still operating below the choked condition at this speed.

The manner in which differences in compressor characteristics among the engines and associated interactions of the other components affect the total pressure ratio P_4/P_1 and total temperature ratio T_4/T_1 across these engines is shown in figure 30. As illustrated, the engine pressure ratios rose considerably more rapidly above rated corrected speed for the centrifugal-flow engines than for the axial-flow engines. Although there was no consistent trend in engine temperature ratio with engine type, the effect of this variable on thrust is considerably less than that of engine pressure ratio. It is the summation of these differences in trends from one engine to another, in addition to differences in air flow characteristics, which account for the marked differences in the ratio of maximum altitude corrected thrust to rated sea-level thrust.

It may therefore be expected that an engine designed for a high air flow per unit flow area, and consequently operating with the flow restricted by inlet choking at rated corrected speed and above, will have a considerably lower thrust at high altitude than an engine with equal sea-level thrust, but designed for a sufficiently low air flow per unit flow area to permit operation at rated corrected speed or above with the inlet unchoked. This characteristic is an important consideration both in engine design and in selection of an engine for a high-altitude aircraft.

CONCLUDING REMARKS

The compressor and the combustor are the only two engine components found to have performance characteristics which were affected over a wide range of altitudes. Two engines exhibited a slight decrease in turbine efficiency, and two had a slight rise in combustor total-pressure-loss ratio at very low engine-inlet pressures, corresponding to flight at altitudes above 50,000 feet. The reduction in compressor efficiency and corrected air flow with Reynolds number index and the reduction in combustion efficiency with reduced altitude pressure are the factors which result in failure of engine performance to generalize for all altitudes and which therefore have a detrimental effect on the altitude performance of turbo-jet engines. In general, the effect is to increase the turbine-outlet

temperature at rated engine speed as the altitude is raised; a speed reduction is thus required to avoid exceeding the turbine temperature limit. The attendant reductions in compressor efficiency and corrected air flow at reduced Reynolds number indices reduce the thrust below the value predicted from a sea-level performance calibration. Also, the combined effects of reduced compressor and combustor efficiencies at high altitudes result in an appreciable increase in specific fuel consumption above the predicted values.

An altitude effect which was found to be of considerably greater importance than the effect of Reynolds number index was the corrected engine speed effect. It was found that the rate of increase in corrected net thrust with corrected engine speed, and consequently the rate of thrust decay with altitude, differed considerably from one engine to another. When the five engines discussed were assumed to have equal thrusts at sea level, the maximum thrust at an altitude of 45,000 feet differed from one engine to another by as much as 26 percent because of the corrected engine speed effect alone. The combined corrected engine speed effect and Reynolds number effects resulted in differences in maximum thrust at this altitude of as much as 31 percent between the engines having the highest and lowest thrusts. The corrected engine speed effect is attributable to the compressor air flow and efficiency characteristics and attendant interaction of the other components. The engines with compressors designed to handle a high air flow per unit flow area, and which consequently have some of the stages choked at high engine speeds, exhibited a more rapid thrust decay with altitude than those designed for lower air flows. It is therefore important that these characteristics be considered when the initial design criteria for an engine and compressor are being established. Furthermore, when an engine is selected for a specific mission, the choice should be based on the performance at design altitude rather than on the sea-level rated thrust and specific fuel consumption.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio.

APPENDIX - CALCULATIONS

Symbols

The following symbols are used in this report:

A	cross-sectional area, sq ft
B	thrust scale or thrust diaphragm reading, lb
D	external drag of installation, lb
d	diameter, ft
F_j	jet thrust, lb
F_n	net thrust, lb
f/a	fuel-air ratio
g	acceleration due to gravity, 32.2 ft/sec ²
H	total enthalpy, Btu/lb
H_F	enthalpy of fuel components in products of combustion, Btu/lb
h_c	lower heating value of fuel, Btu/lb
M	Mach number
N	engine speed, rpm
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	universal gas constant, 53.4 ft-lb/(lb)(°R)
Re	Reynolds number
T	total temperature, °R
T_i	indicated temperature, °R
t	static temperature, °R
V	velocity, ft/sec

W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
W_g	gas flow, lb/sec
γ	ratio of specific heats for gases
δ	ratio of engine inlet absolute total pressure to absolute total pressure of NACA standard atmosphere at sea level
η	efficiency
θ	ratio of engine inlet absolute total temperature to absolute total temperature of NACA standard atmosphere at sea level
μ	absolute viscosity, slugs/ft sec
ρ	density, slugs/cu ft
ϕ	ratio of air absolute viscosity at engine-inlet total temperature to air absolute viscosity at total temperature of NACA standard atmosphere at sea level

Subscripts:

0	free stream
1	engine inlet
2	compressor outlet
3	turbine inlet
4	turbine outlet
5	tail-pipe nozzle outlet
a	air
b	combustor
c	compressor
e	engine
f	fuel

m fuel manifold
 s tail-pipe seal at bulkhead
 t turbine
 x inlet duct at slip joint

Generalized Performance Variables

The generalized engine performance variables used in this report are defined as follows:

$\frac{F_j + A_5 P_0}{\delta}$ corrected jet thrust parameter, lb
 F_n/δ corrected net thrust, lb
 $N/\sqrt{\theta}$ corrected engine speed, rpm
 T_4/θ corrected turbine-outlet total temperature, °R
 $\frac{W_a \sqrt{\theta}}{\delta}$ corrected air flow, lb/sec
 $W_F/(\delta \sqrt{\theta})$ corrected fuel flow, lb/hr
 $W_F/F_n \sqrt{\theta}$ corrected net thrust specific fuel consumption,
 lb/(hr)(lb thrust)

Methods of Calculation

Total temperature. - Total temperatures were calculated from the indicated temperatures, using a thermocouple recovery factor of 0.85, and the values of pressure and ratio of specific heats at the respective stations in the engines.

$$T = \frac{T_1 \left(\frac{P}{P_1} \right)^{\frac{\gamma-1}{\gamma}}}{1 + 0.85 \left[\left(\frac{P}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \quad (1)$$

Air flow. - For the axial-flow engines, the air flow was calculated from pressure and temperature measurements obtained at the engine inlet (station 1)

$$W_a = P_1 A_1 \sqrt{\frac{2\gamma g}{(\gamma-1)RT_1} \left[\left(\frac{P_1}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \left(\frac{P_1}{P_1} \right)^{\frac{\gamma-1}{\gamma}}} \quad (2)$$

The same expression was used for calculating the centrifugal flow engine air flows with the tail-pipe outlet measurements (station 5) substituted in place of the engine inlet values.

Compressor efficiency. - The adiabatic temperature-rise compressor efficiency for both the full-scale engine and compressor component installations was calculated by the following equation:

$$\eta_c = \frac{\left(\frac{P_2}{P_1} \right)^{\frac{\gamma_c-1}{\gamma_c}} - 1}{\frac{T_2}{T_1} - 1} \quad (4)$$

where γ_c is the ratio of specific heats corresponding to the average total temperature of the air flowing through the compressor.

Turbine efficiency. - Turbine efficiency was calculated from the equation:

$$\eta_t = \frac{1 - \frac{T_4}{T_3}}{1 - \left(\frac{P_4}{P_3} \right)^{\frac{\gamma_t-1}{\gamma_t}}} \quad (5)$$

where γ_t is the ratio of specific heats corresponding to the average total temperature of the gas flowing through the turbine. To obtain turbine-inlet temperature, the enthalpy at the turbine inlet was calculated from the turbine-outlet temperature and compressor temperature rise; compressor and turbine work were assumed equal.

$$H_3 = \frac{W_a}{W_g} (H_2 - H_1) + H_4 \quad (6)$$

Turbine-inlet temperature was then determined by the use of enthalpy charts.

Combustion efficiency. - Combustion efficiency was calculated from the enthalpy rise across the combustors by the following equation:

$$\eta_b = \frac{H_{a,3} + f/a (H'_{f,3} - H_{f,m}) - H_{a,2}}{f/a h_c} \quad (7)$$

The enthalpy of the fuel components in the products of combustion $H'_{f,3}$ was determined from the hydrogen-carbon ratio of the fuel and the calculated turbine-inlet temperature by the method described in reference 19.

Thrust. - For engines installed in the altitude wind tunnel, the measured thrust was determined from balance scale measurements by use of the relation

$$F_j = B + D + \frac{W_a}{g} V_x + A_x (p_x - p_0)$$

where the external drag D was determined from power-off ,

Because there was no measurable external drag or initial momentum for engines installed in the altitude chamber, the measured jet thrust was determined from force measurements on the thrust diaphragm by the relation

$$F_j = B + A_s (P_1 - p_0) \quad (9)$$

where P_1 was taken as the static pressure in the inlet section of the chamber.

The calculated jet thrust, which was determined from pressure and temperature measurements at the turbine outlet, was calculated by the relation

$$F_j = \frac{W_g}{g} \sqrt{\frac{2\gamma_4}{\gamma_4 - 1} \frac{gRT_4}{\gamma_4} \left[1 - \left(\frac{p_0}{P_4} \right)^{\frac{\gamma_4 - 1}{\gamma_4}} \right]} \quad (10)$$

Net thrust for each engine was calculated using the measured thrust in the following equation:

$$F_n = F_j - \frac{W_a}{g} V_0 \quad (11)$$

where free-stream velocity V_0 was calculated from engine inlet total pressure P_1 and temperature T_1 and free-stream static pressure p_0 , assuming complete free-stream ram pressure recovery at the engine inlet.

Reynolds number index. - In developing the expression for Reynolds number index (reference 8), Reynolds number of the engine may be expressed as:

$$Re = \frac{\rho_1 V_1 d_e}{\mu_1} \quad (12)$$

In the case of a turbojet engine, it is convenient to consider the mass velocity $\rho_1 V_1$ as the mass flow per unit frontal area W_a/A_e . The Reynolds number is then

$$Re = \frac{d_e (W_a/A_e)}{\mu_1} \quad (13)$$

Reynolds number is not a convenient parameter because mass flow is a function not only of the pressure and temperature of the inlet air, but is also dependent on two other independent variables, corrected engine speed and compressor pressure ratio. A more convenient parameter for considering the effects of fluid viscosity is

$$\frac{d_e P_1}{\mu_1 \sqrt{T_1}} \sqrt{\frac{\gamma}{R}} \quad (14)$$

This parameter is related to the ratio of Reynolds number to Mach number and its value depends only on the condition of the air at the engine inlet. In generalizing engine data, it is convenient to use δ in place of P and θ in place of T . When the same reasoning that led to the development of δ and θ is followed, another quantity Φ , is defined as:

$$\Phi = \frac{\text{viscosity at engine-inlet total temperature}}{\text{viscosity at total temperature of NACA standard sea-level atmosphere}} \quad (15)$$

When the quantities δ , θ , and Φ are used in equation (14) in place of P , T , and μ , respectively, and the constants d_e , γ , and R are omitted, the following form of Reynolds number index is obtained:

$$\text{Reynolds number index} = \frac{\delta}{\Phi \sqrt{\theta}} \quad (16)$$

The value of this Reynolds number index is 1.0 at NACA standard sea-level pressure and temperature.

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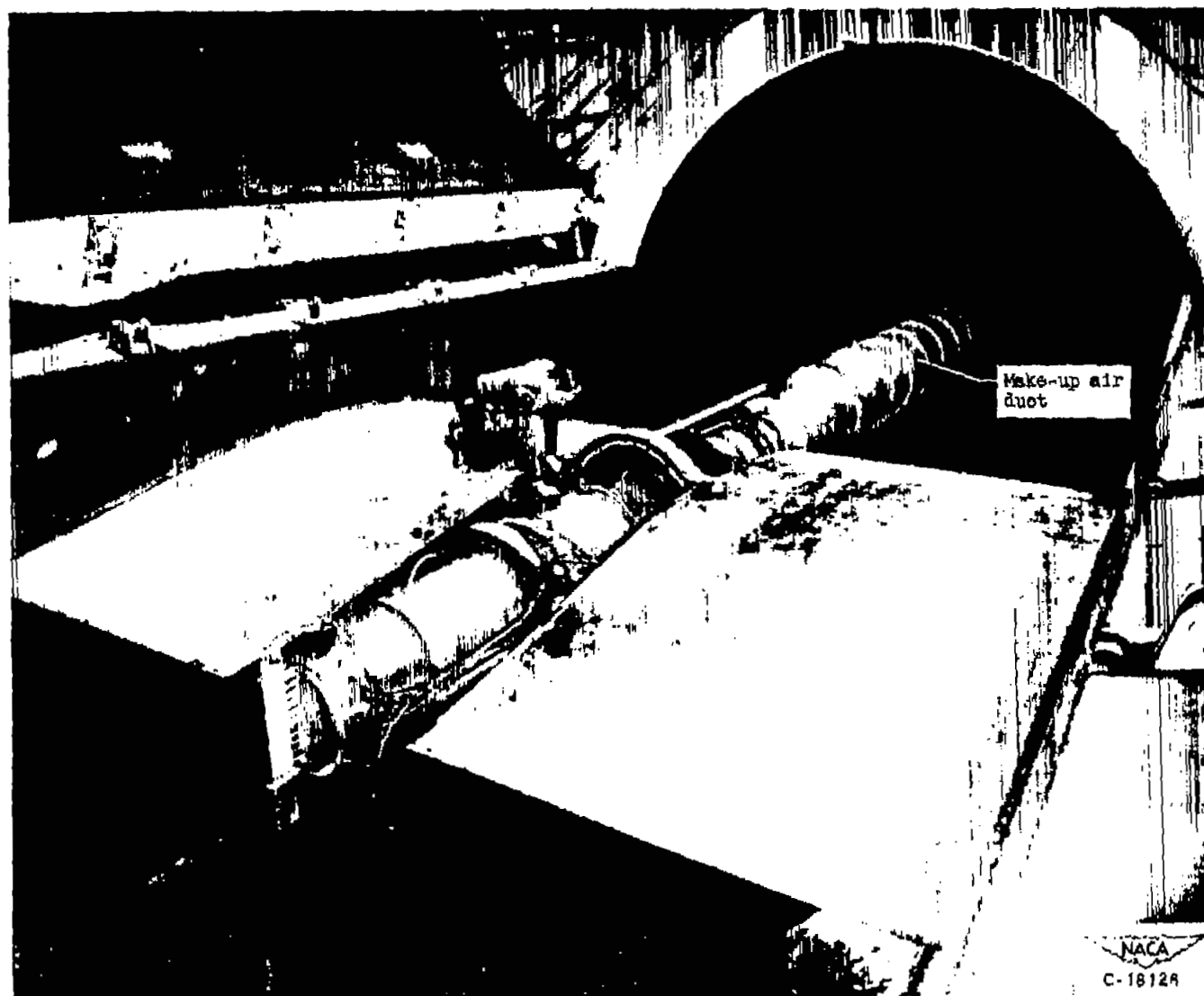


Figure 1. - Installation of turbojet engine in altitude wind tunnel.

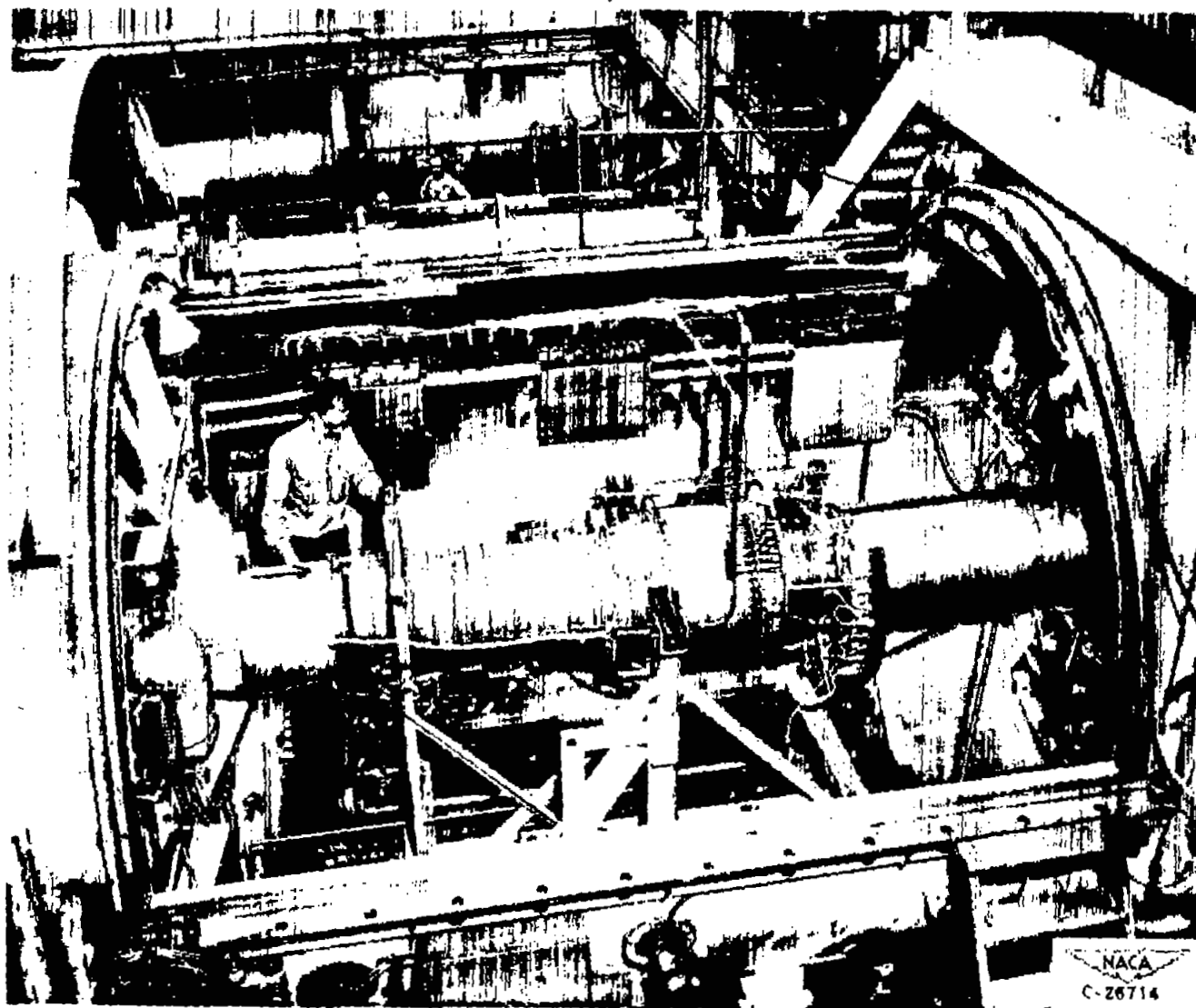


Figure 2. - Installation of turbojet engine in altitude chamber.

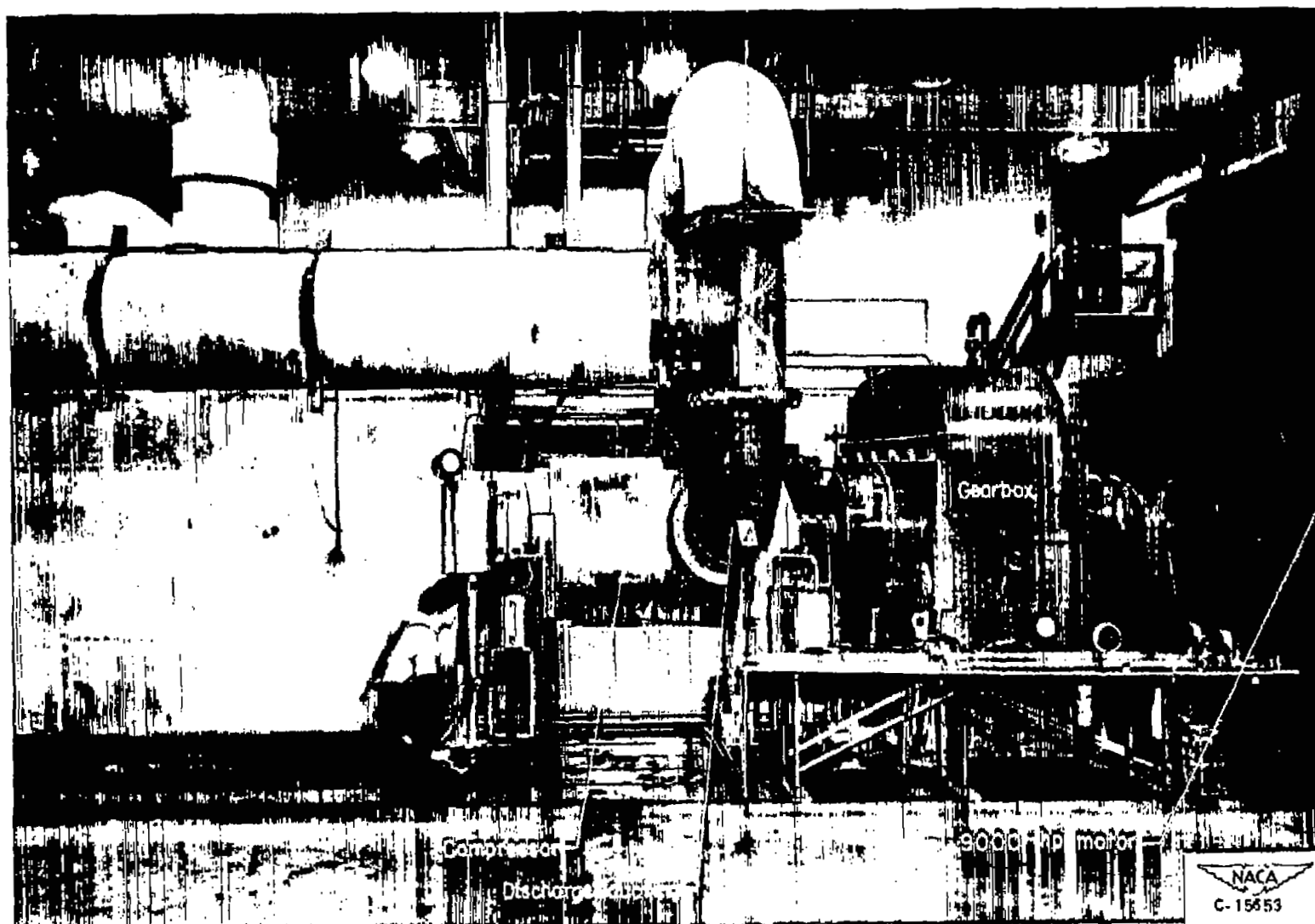
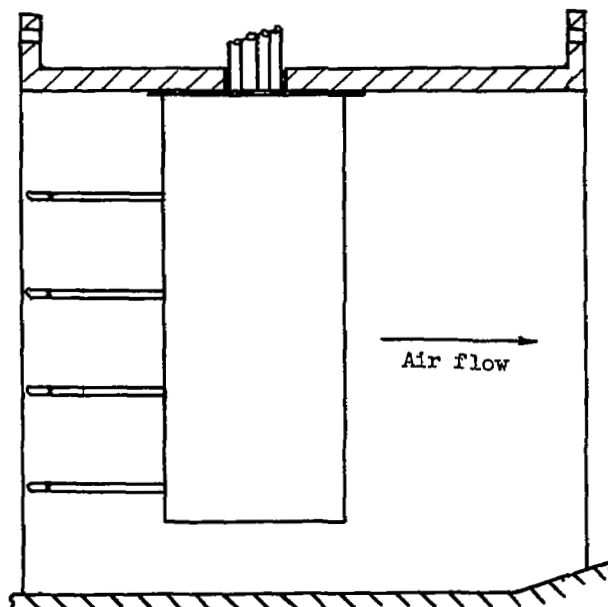
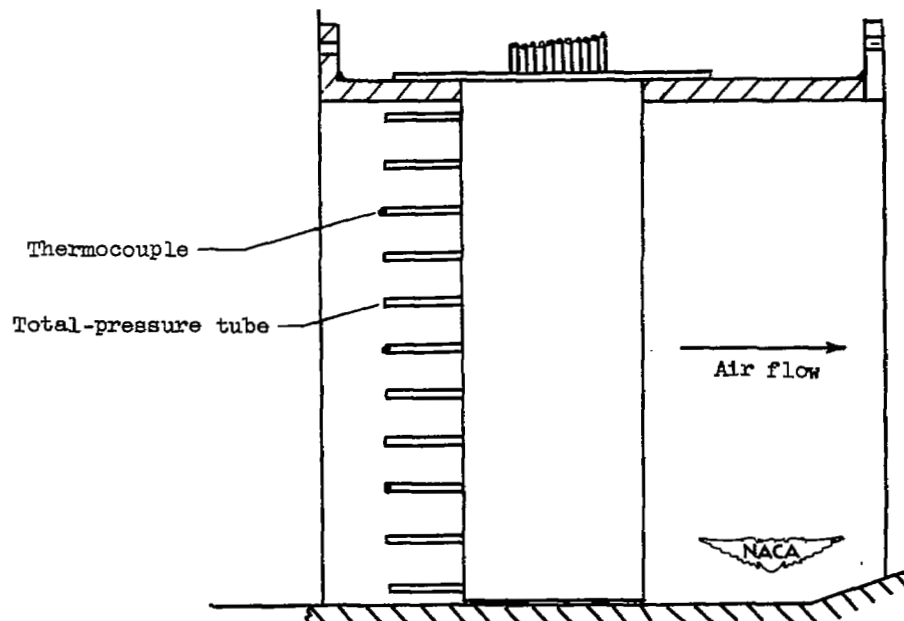


Figure 3. - Setup for investigating performance of axial-flow compressor.

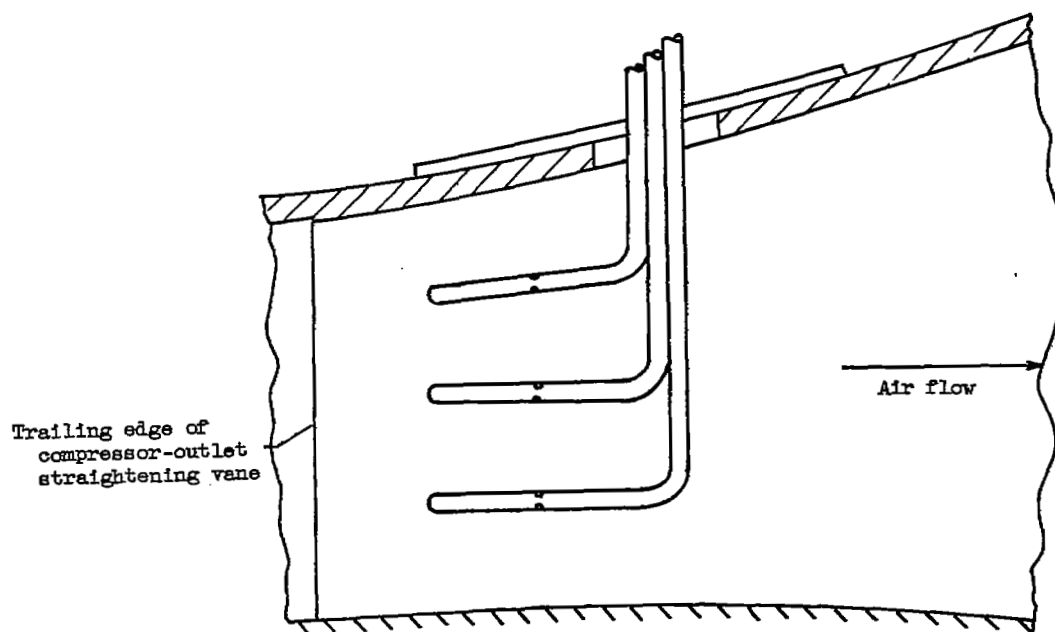


(a) Static pressure tube instrumentation at compressor inlet.

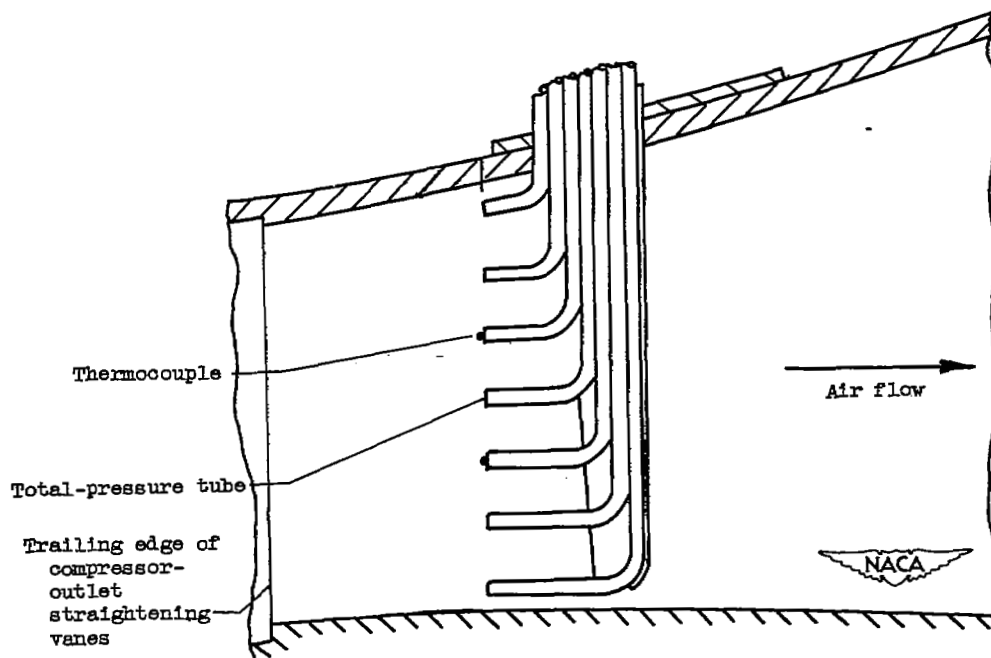


(b) Total-pressure tube and thermocouple instrumentation at compressor inlet.

Figure 4. - Typical survey rake installations.

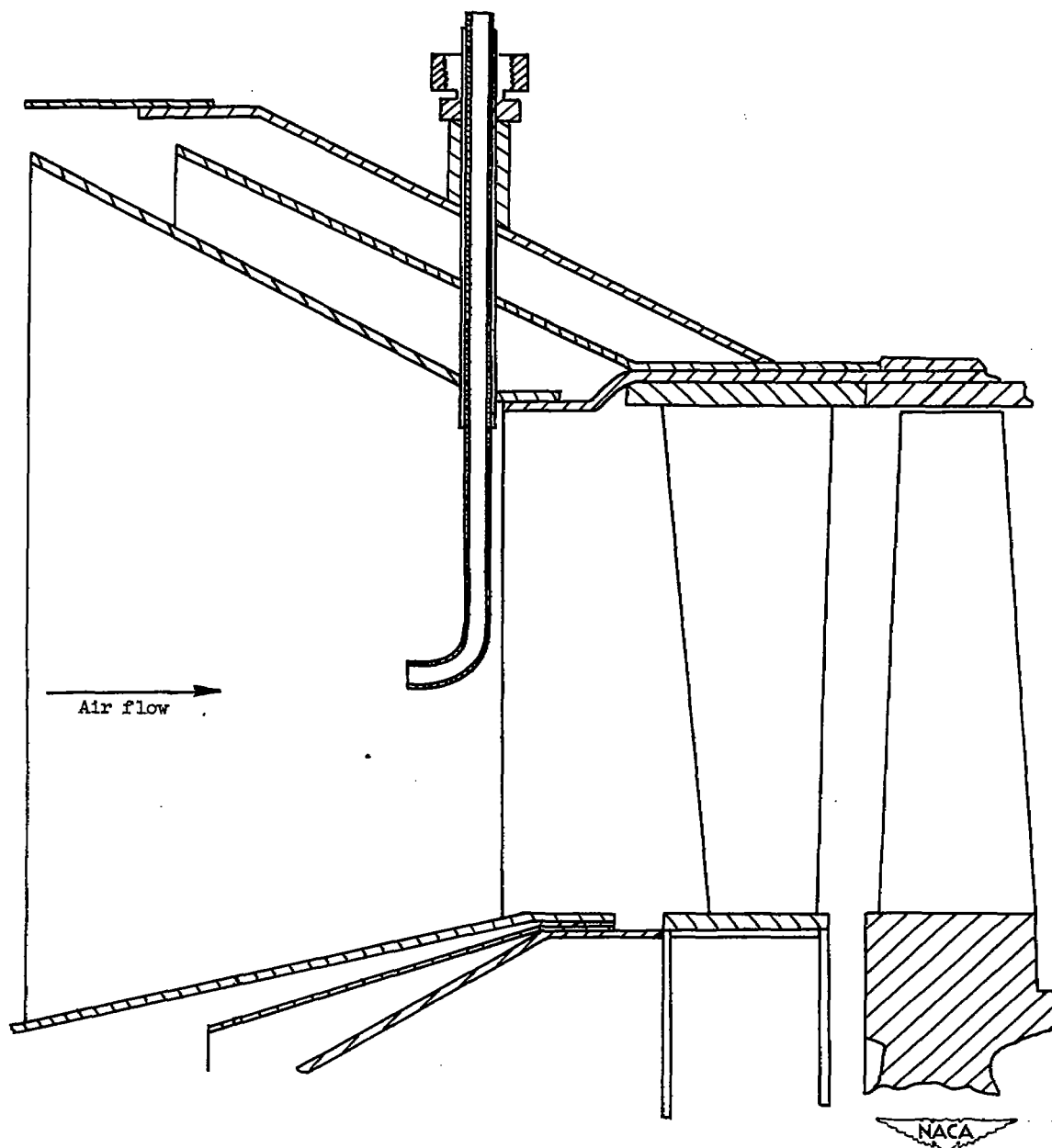


(c) Static-pressure tube instrumentation at compressor outlet.



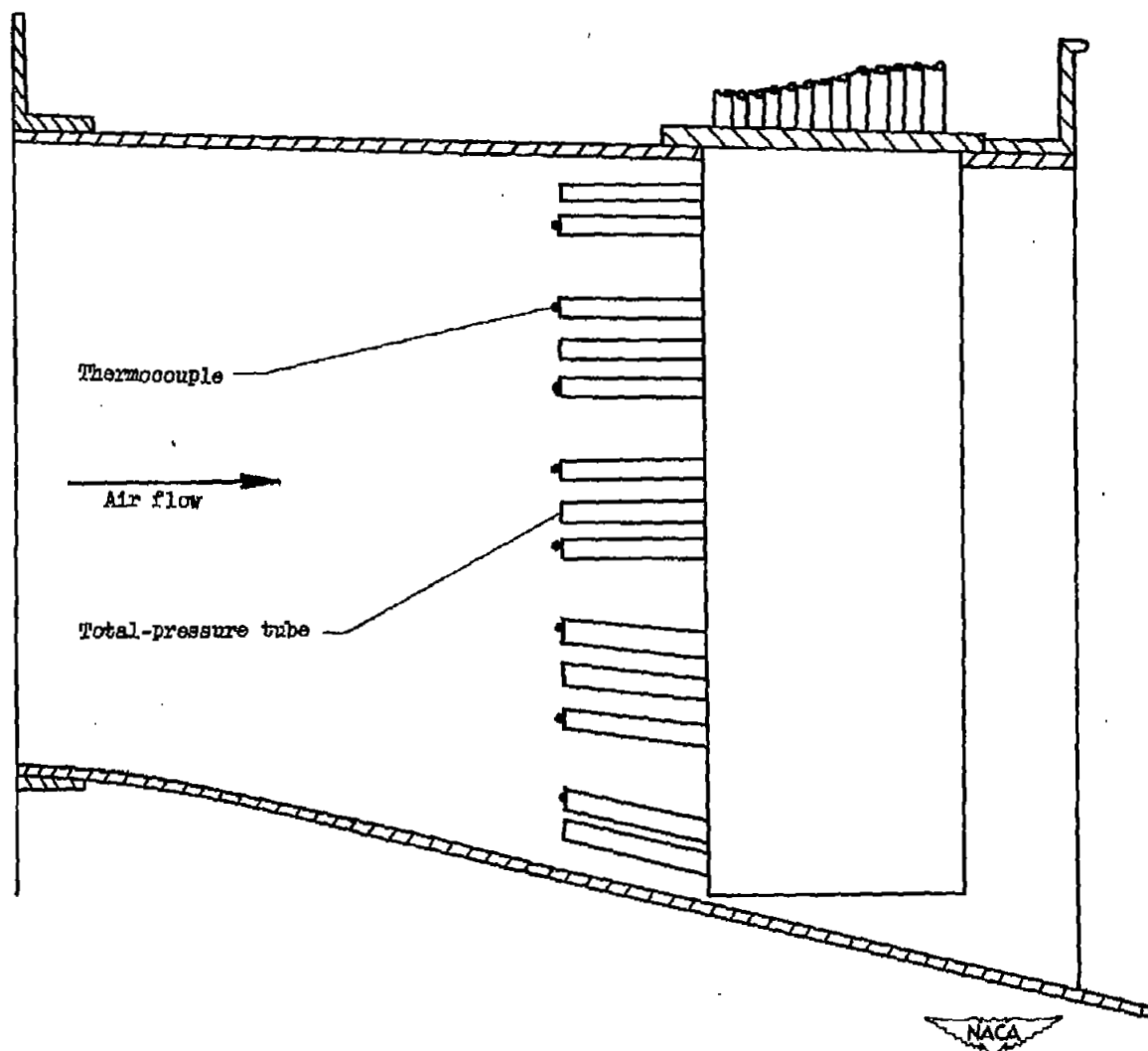
(d) Total-pressure tube and thermocouple instrumentation at compressor outlet.

Figure 4. - Continued. Typical rake installations.



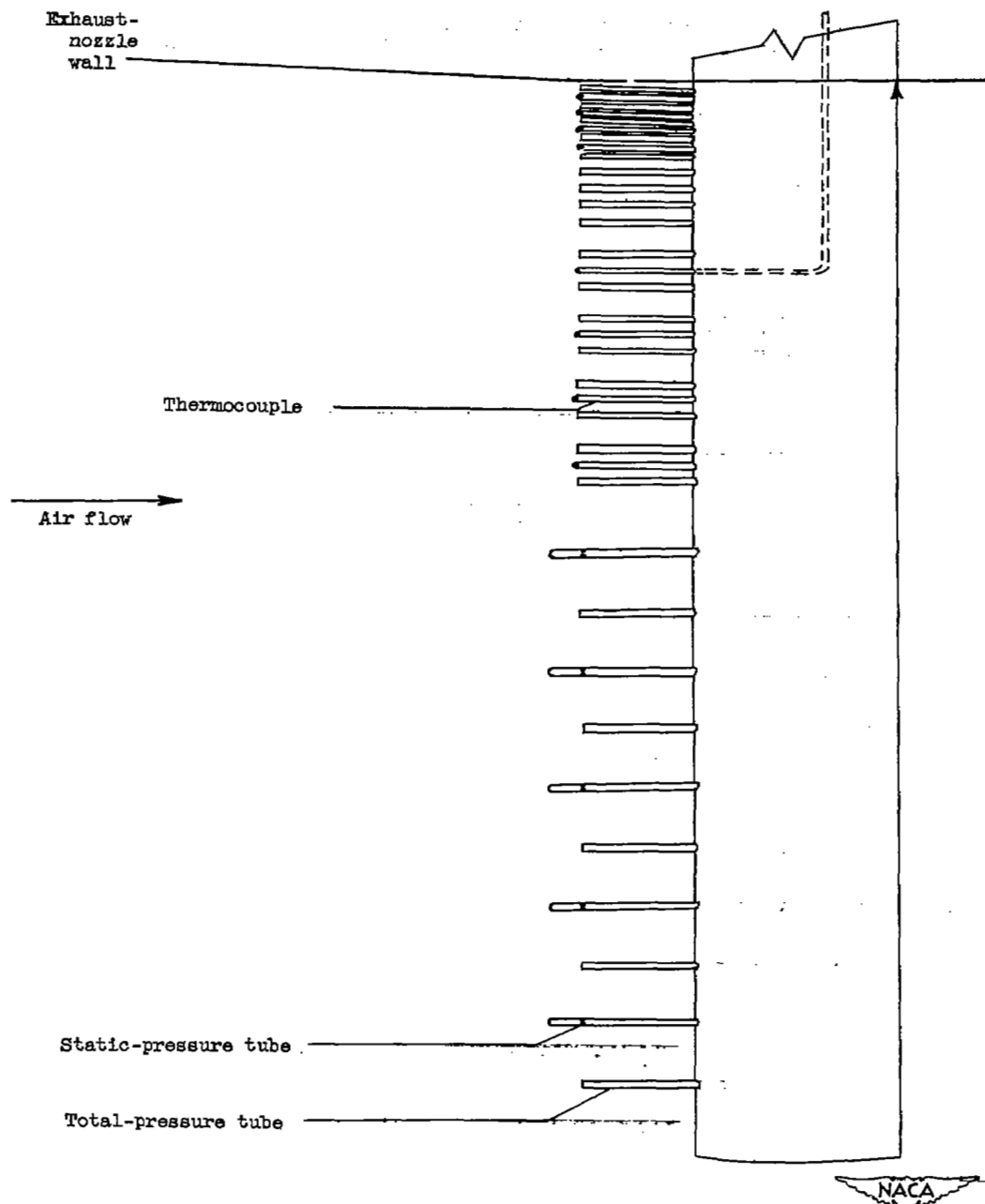
(e) Total-pressure tube instrumentation at turbine inlet.

Figure 4. - Continued. Typical survey rake installations.



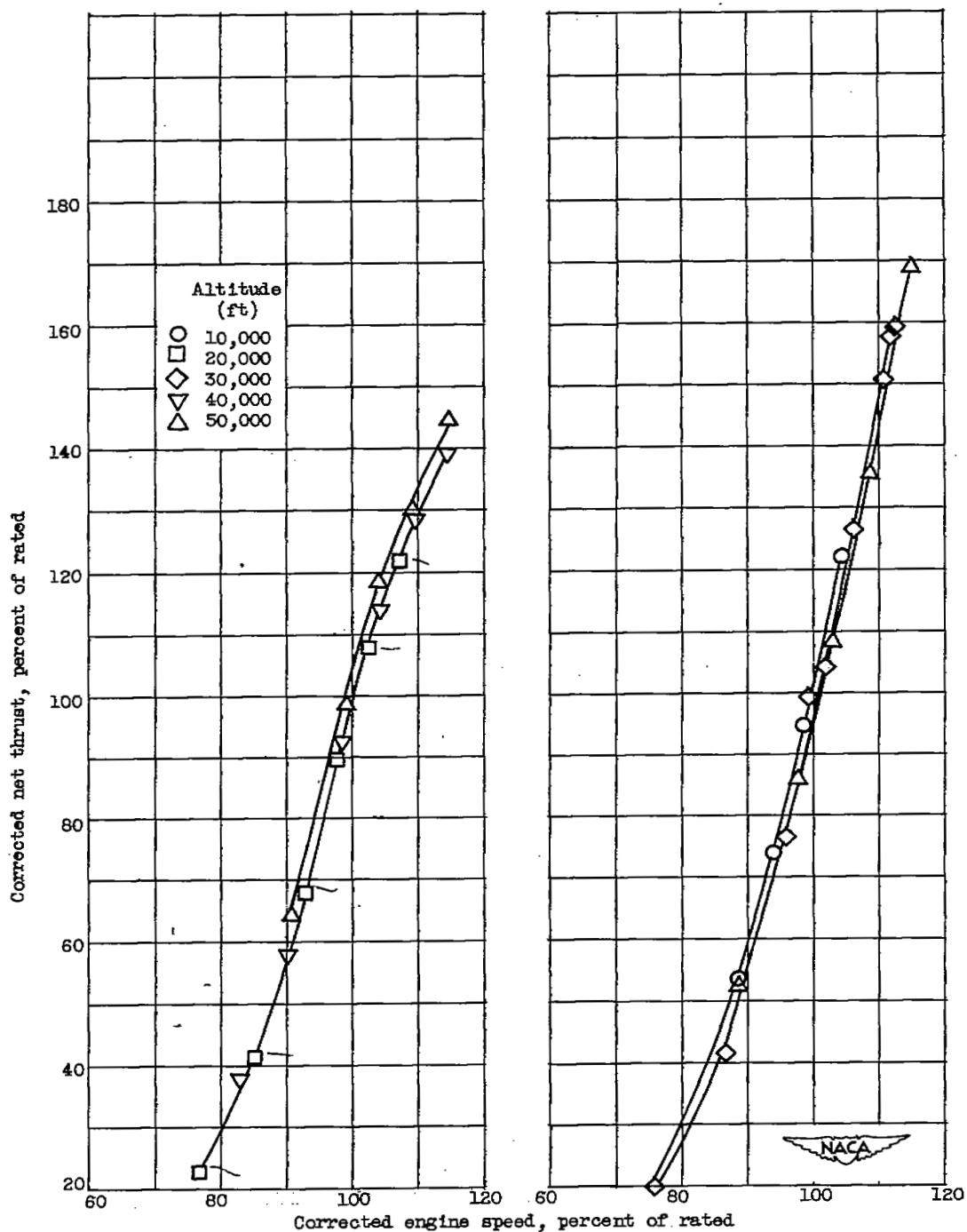
(f) Total-pressure tube and thermocouple instrumentation at turbine outlet.

Figure 4. - Continued. Typical survey rake installations.



(g) Total- and static-pressure tubes and thermocouple instrumentation at exhaust-nozzle outlet.

Figure 4. - Concluded. Typical survey rake installations.



(a) Engine B, axial-flow engine;
flight Mach number, 0.62.

(b) Engine F, centrifugal-flow engine;
flight Mach number, 0.67.

Figure 5. - Effect of altitude on corrected net thrust.

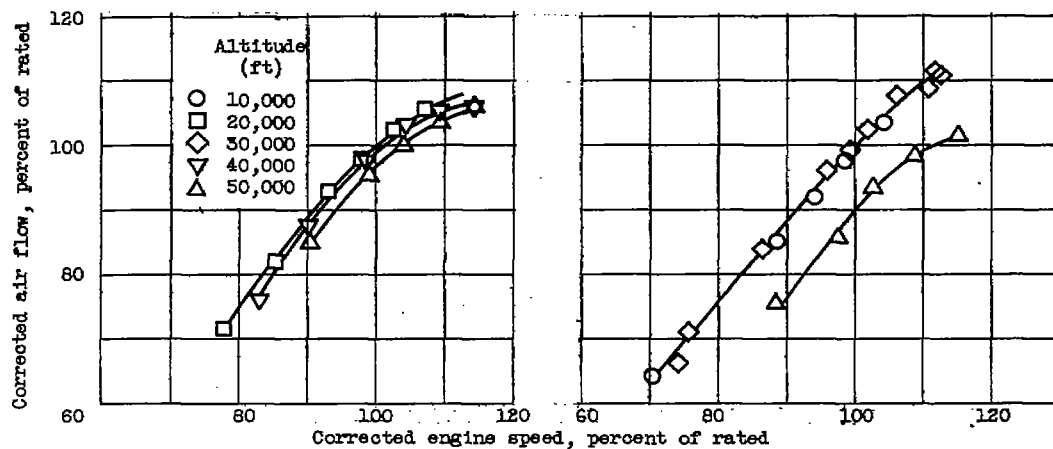


Figure 6. - Effect of altitude on corrected air flow.

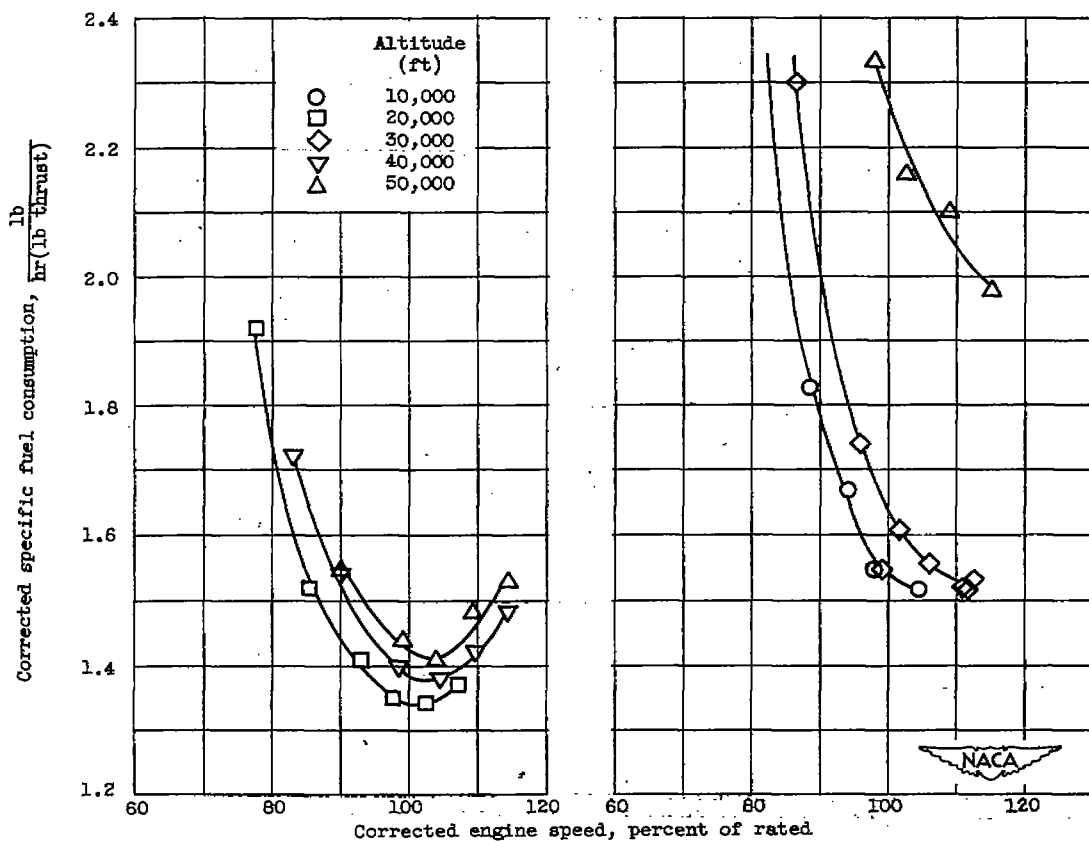
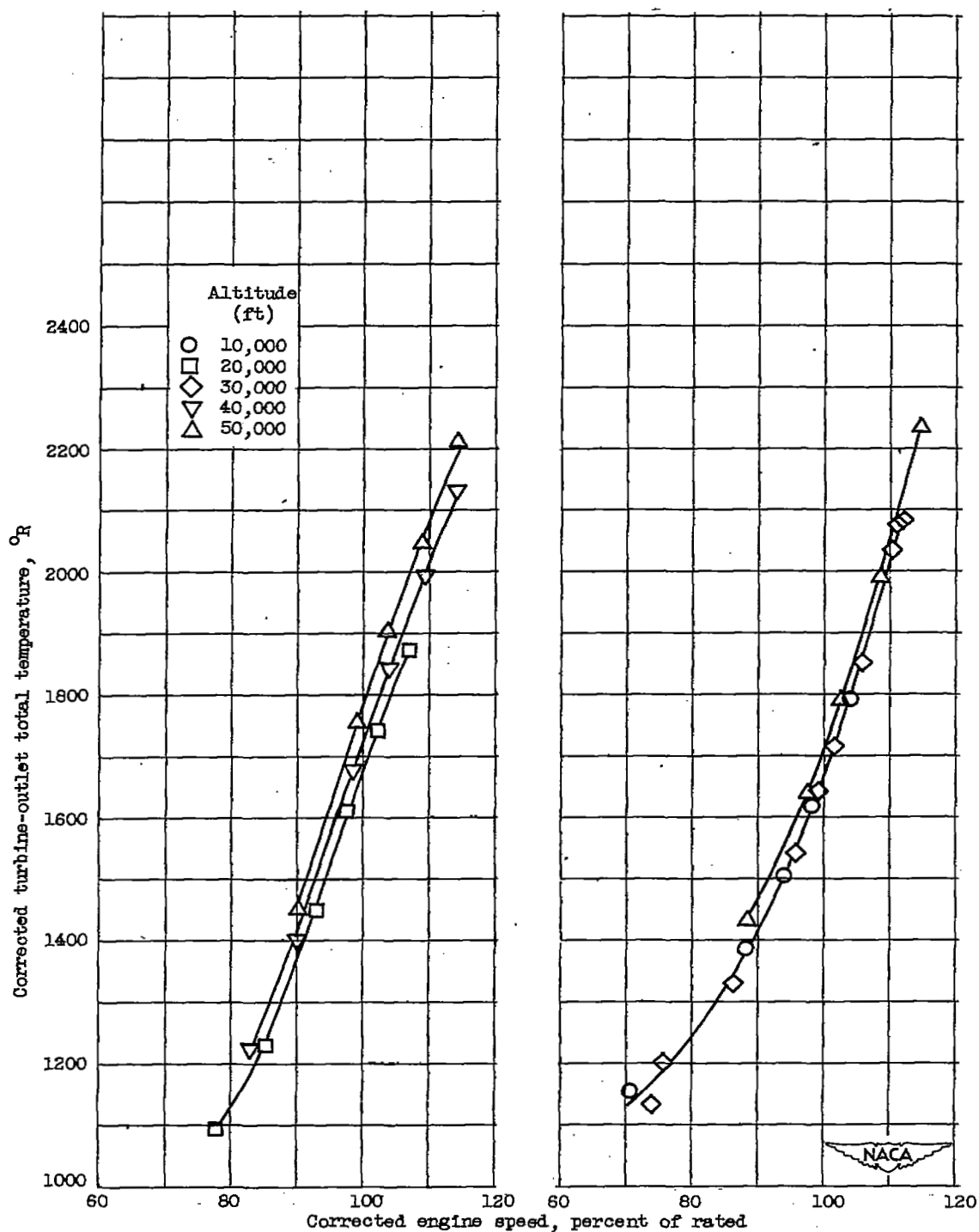


Figure 7. - Effect of altitude on corrected specific fuel consumption.



(a) Engine B, axial-flow engine;
flight Mach number, 0.62

(b) Engine F, centrifugal-flow engine;
flight Mach number, 0.67.

Figure 8. - Effect of altitude on corrected turbine-outlet total temperature.

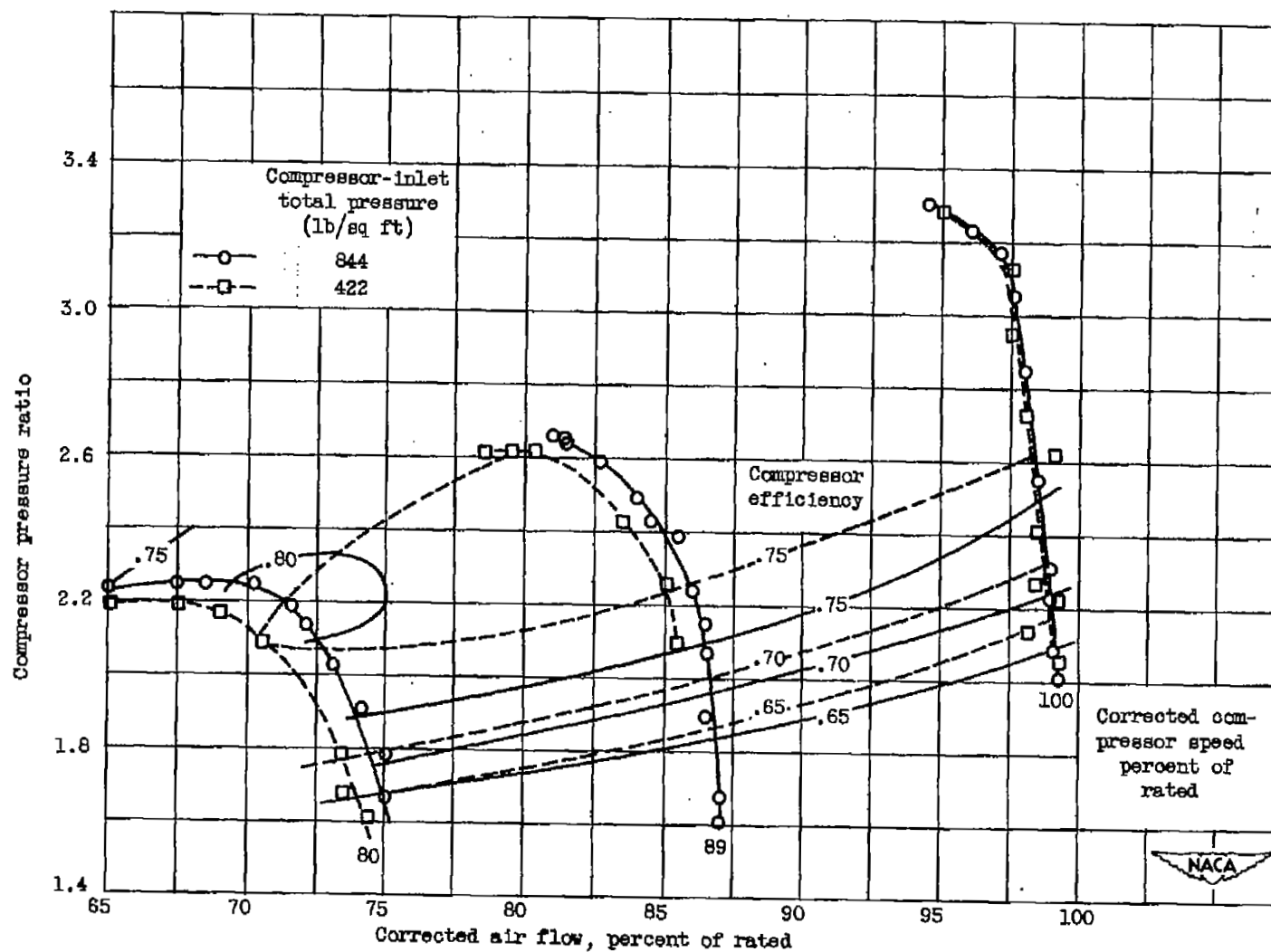
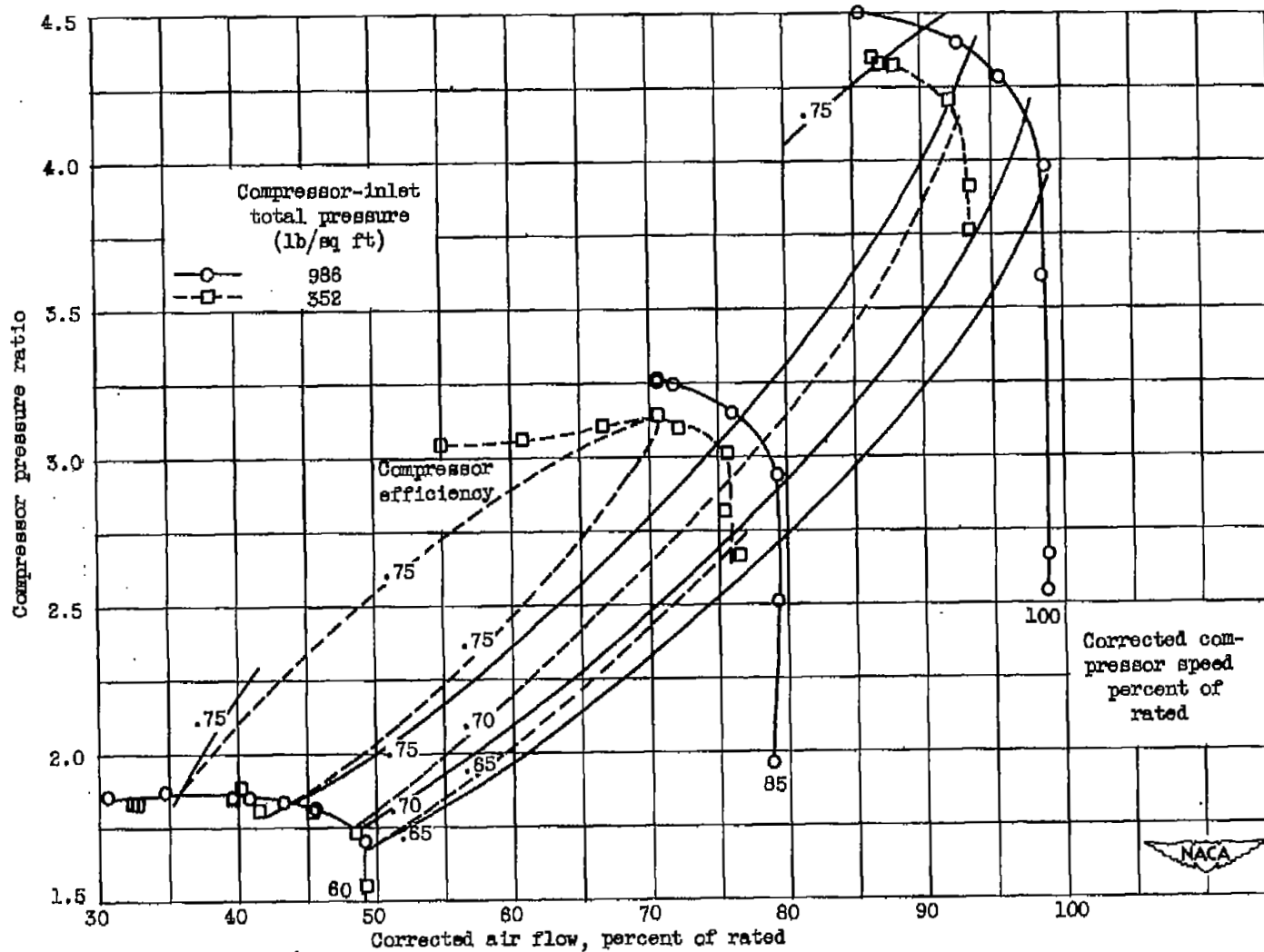


Figure 9. - Effect of inlet pressure on characteristics of compressors investigated in compressor component installations.



(b) Engine F, centrifugal-flow compressor.

Figure 9. - Concluded. Effect of inlet pressure on characteristics of compressors investigated in compressor component installations.

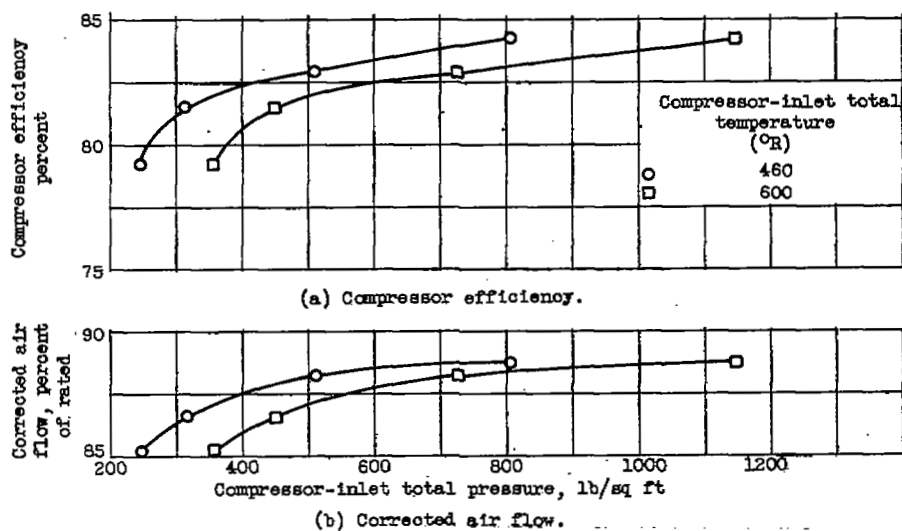


Figure 10. - Variation of axial-flow-compressor performance with inlet conditions. Corrected compressor speed and compressor pressure ratio, constant; engine A.

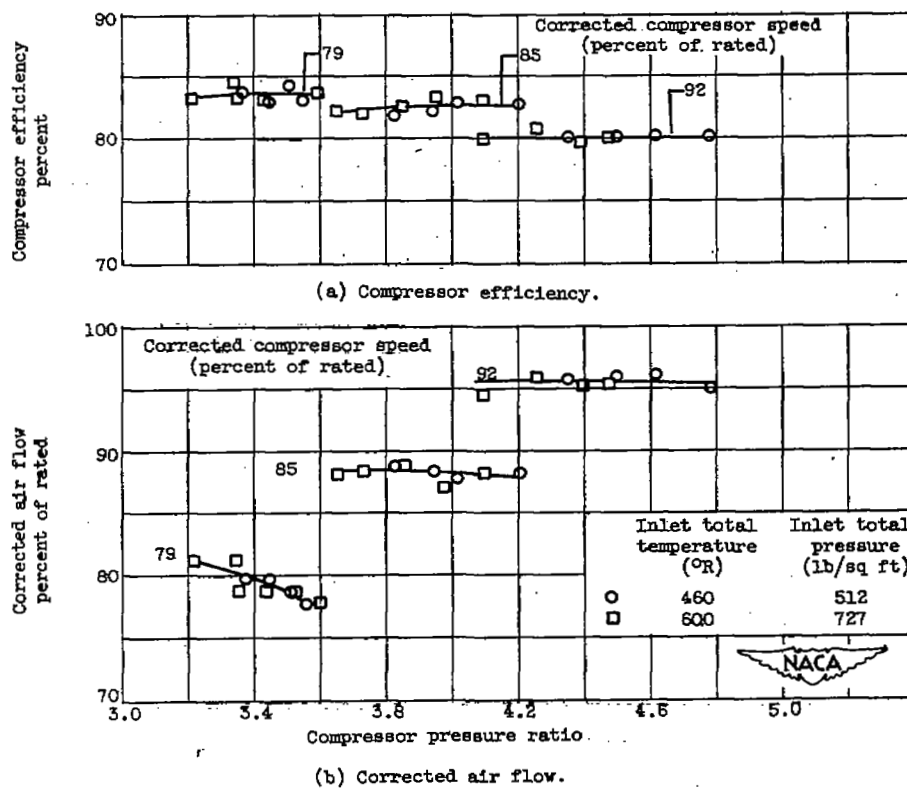
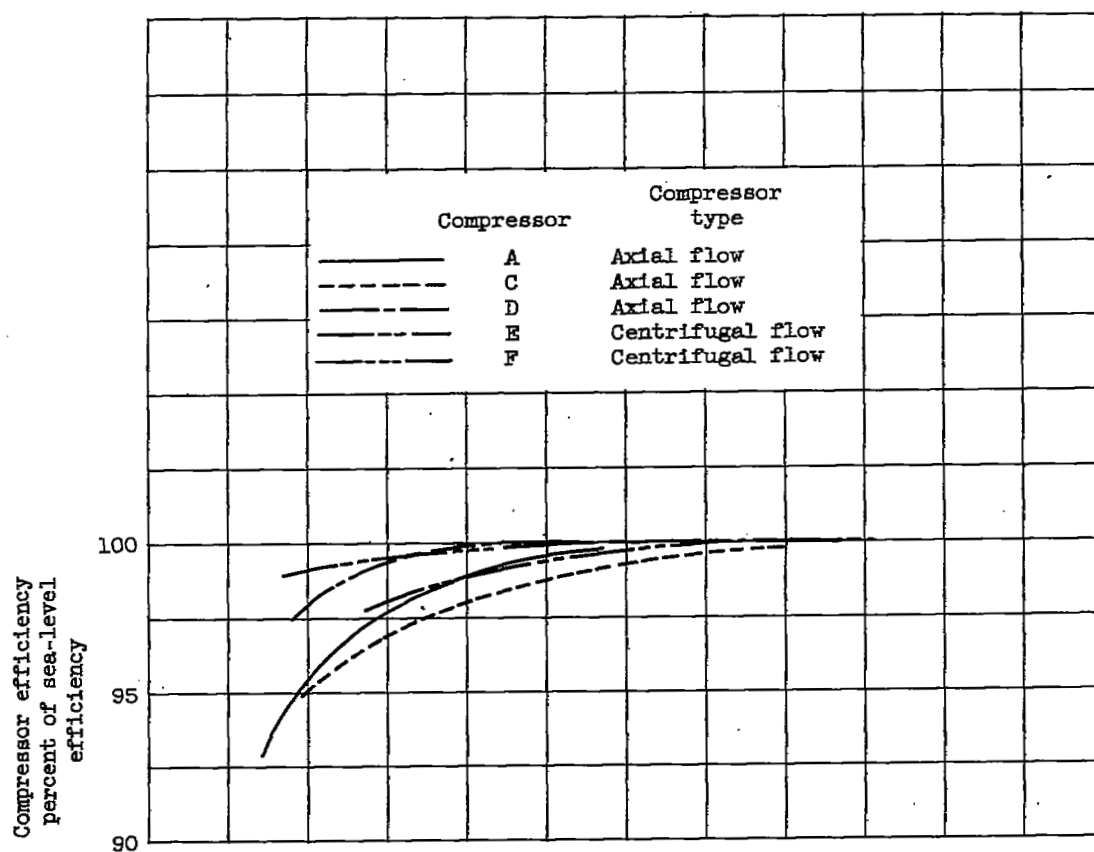
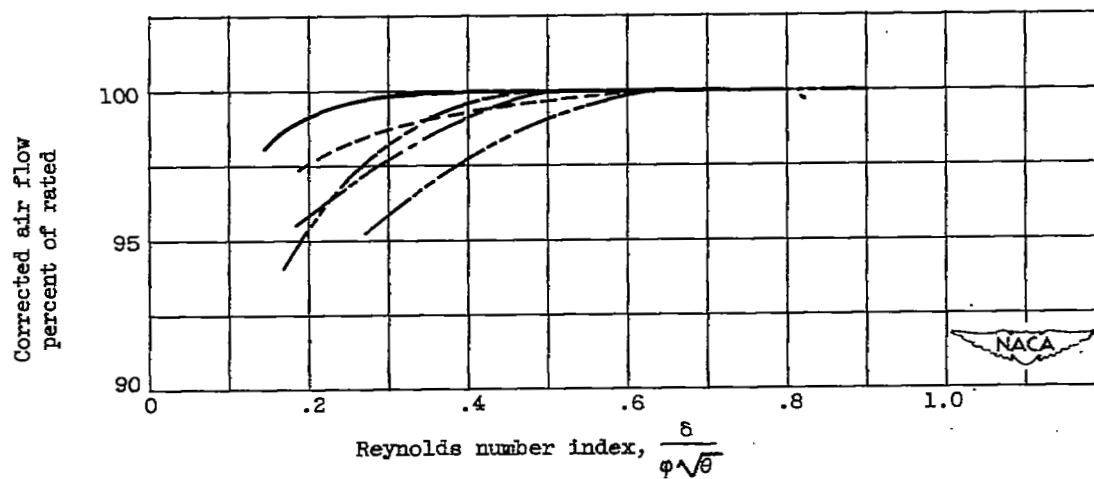


Figure 11. - Effect of inlet conditions on axial-flow-compressor performance. Reynolds number index, 0.282; engine A.



(a) Compressor efficiency.



(b) Corrected air flow.

Figure 12. - Variation of axial- and centrifugal flow compressor performance with Reynolds number index. Corrected compressor speed, rated; pressure ratio, constant.

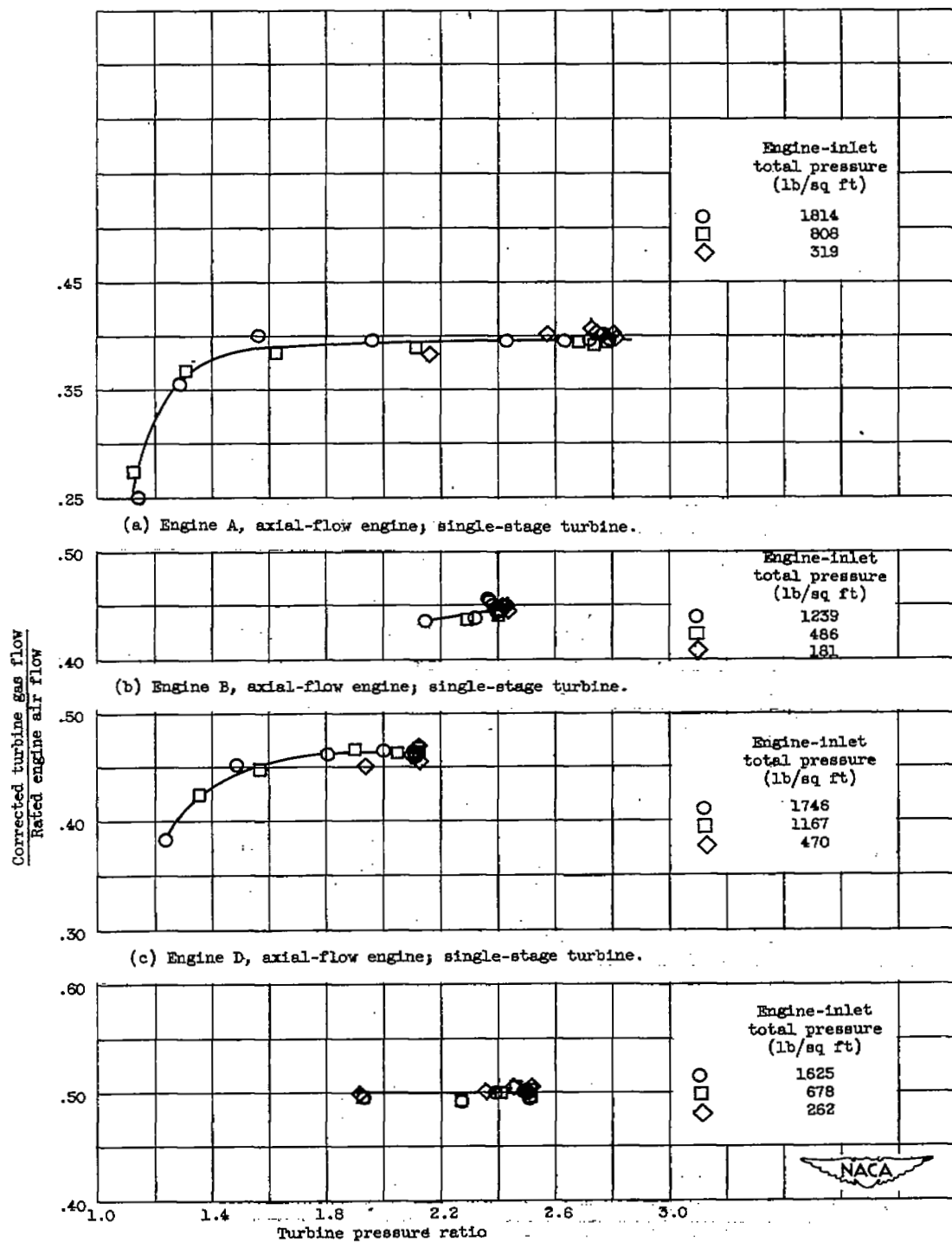
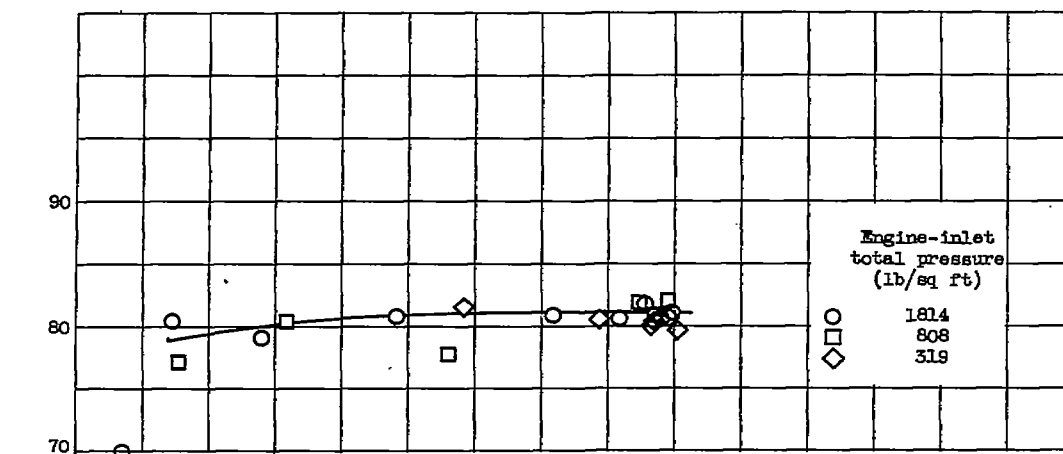
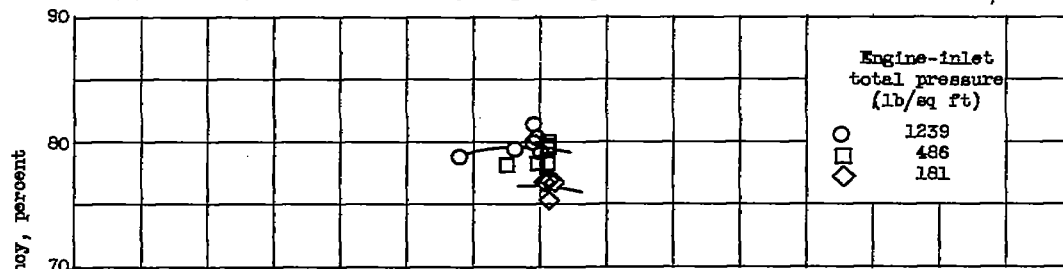


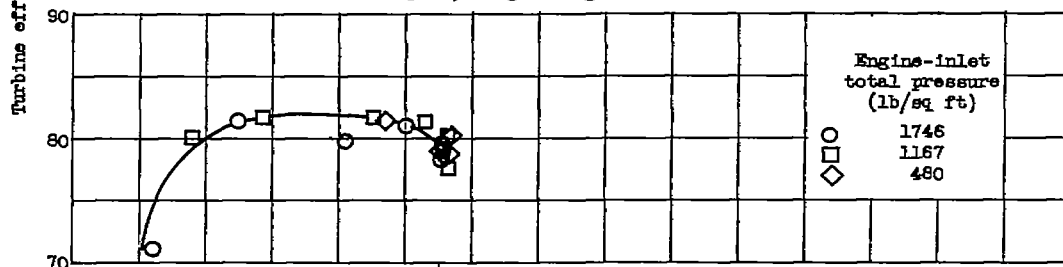
Figure 13. - Effect of altitude pressure on corrected turbine gas flow.



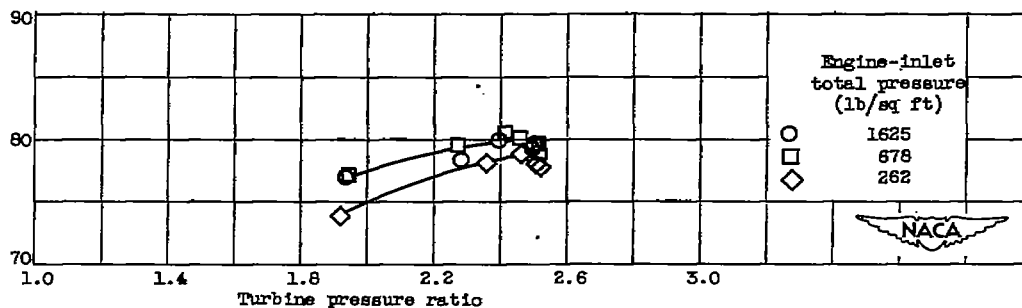
(a) Engine A; axial-flow engine; single-stage turbine.



(b) Engine B; axial-flow engine; single-stage turbine.



(c) Engine D; axial-flow engine; single-stage turbine.



(d) Engine F; centrifugal-flow engine; single-stage turbine.

Figure 14. - Effect of altitude pressure on turbine efficiency.

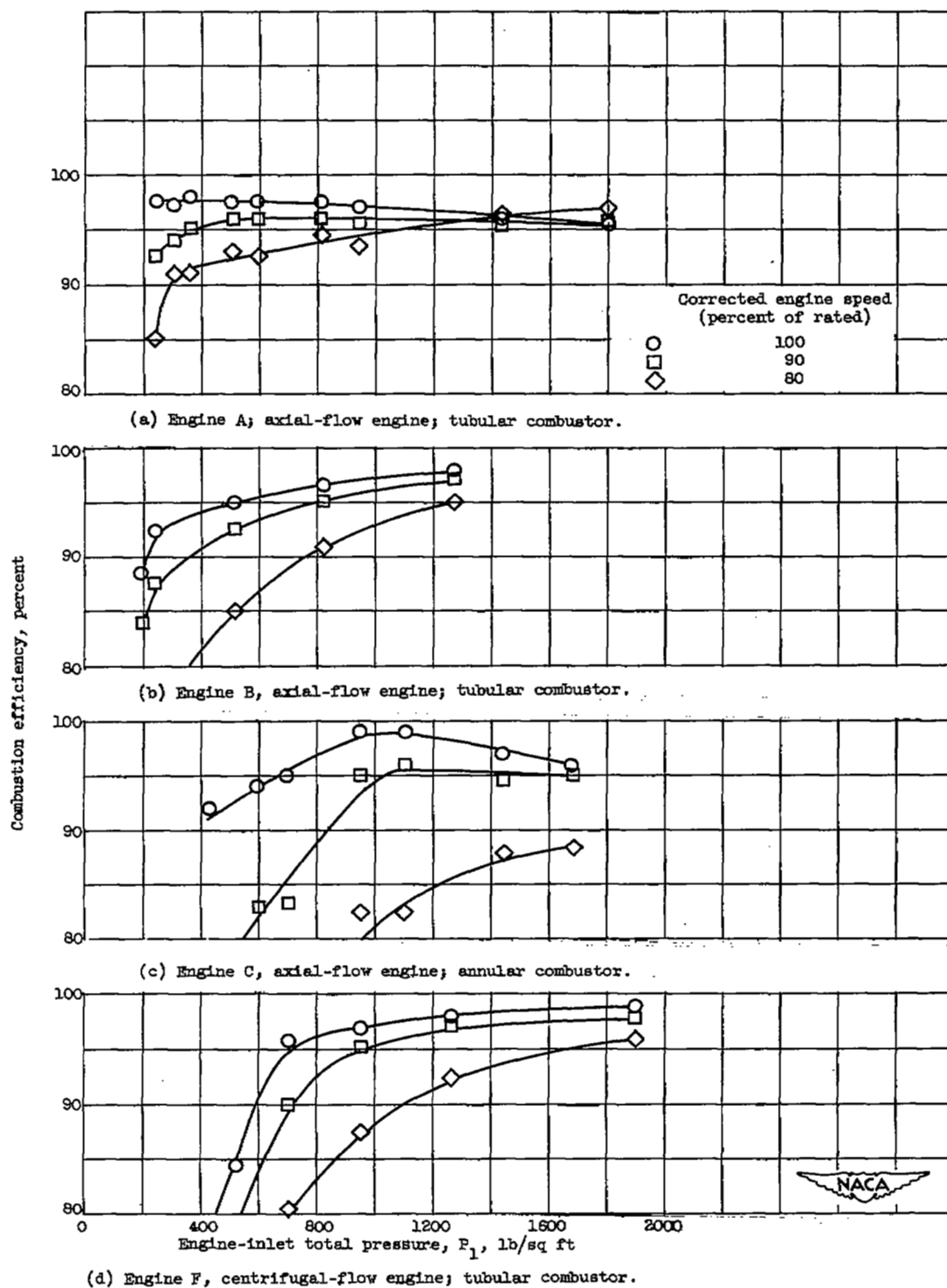


Figure 15. - Variation of combustion efficiency with engine-inlet total pressure at constant corrected engine speed for engines having tubular and annular combustors.

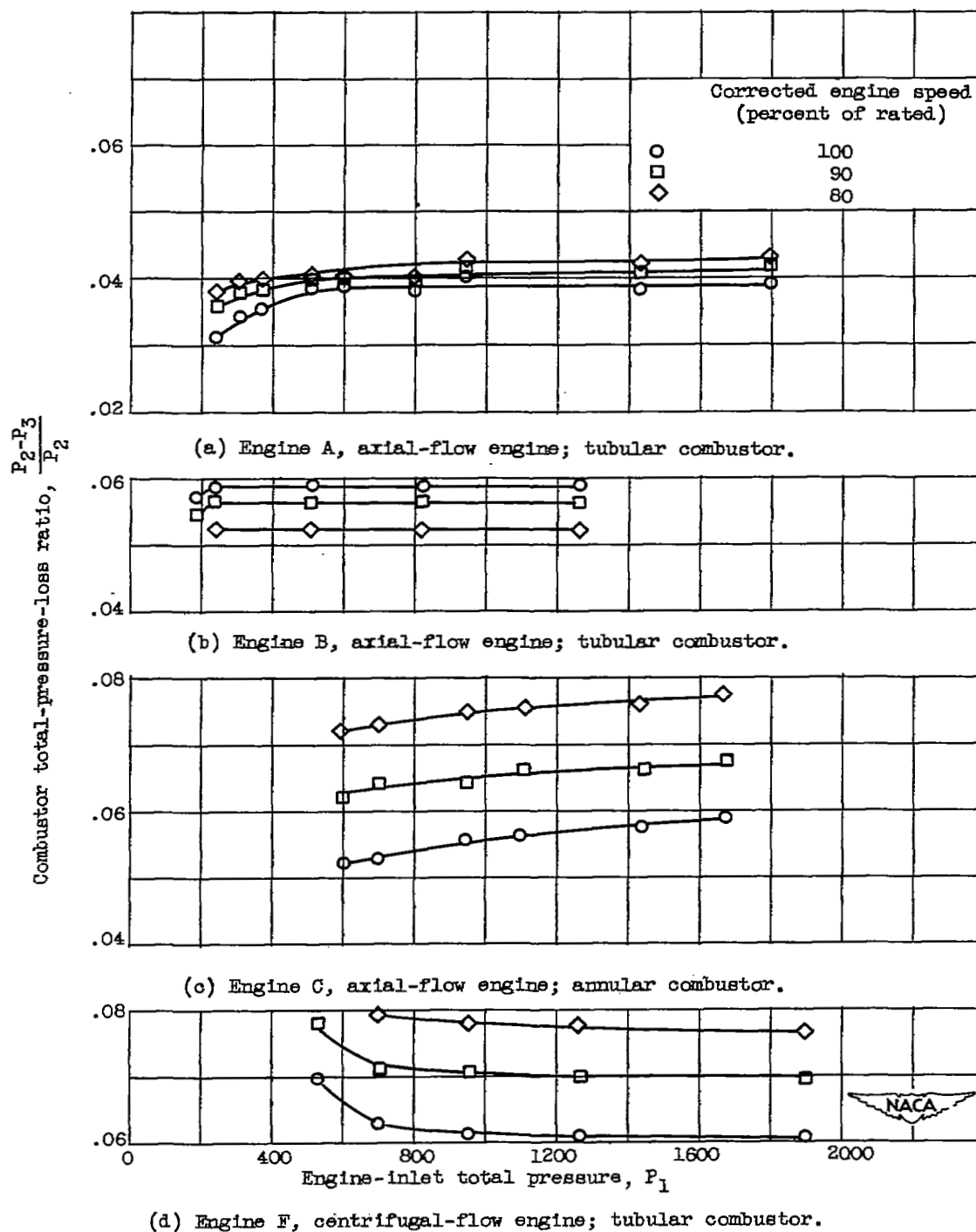
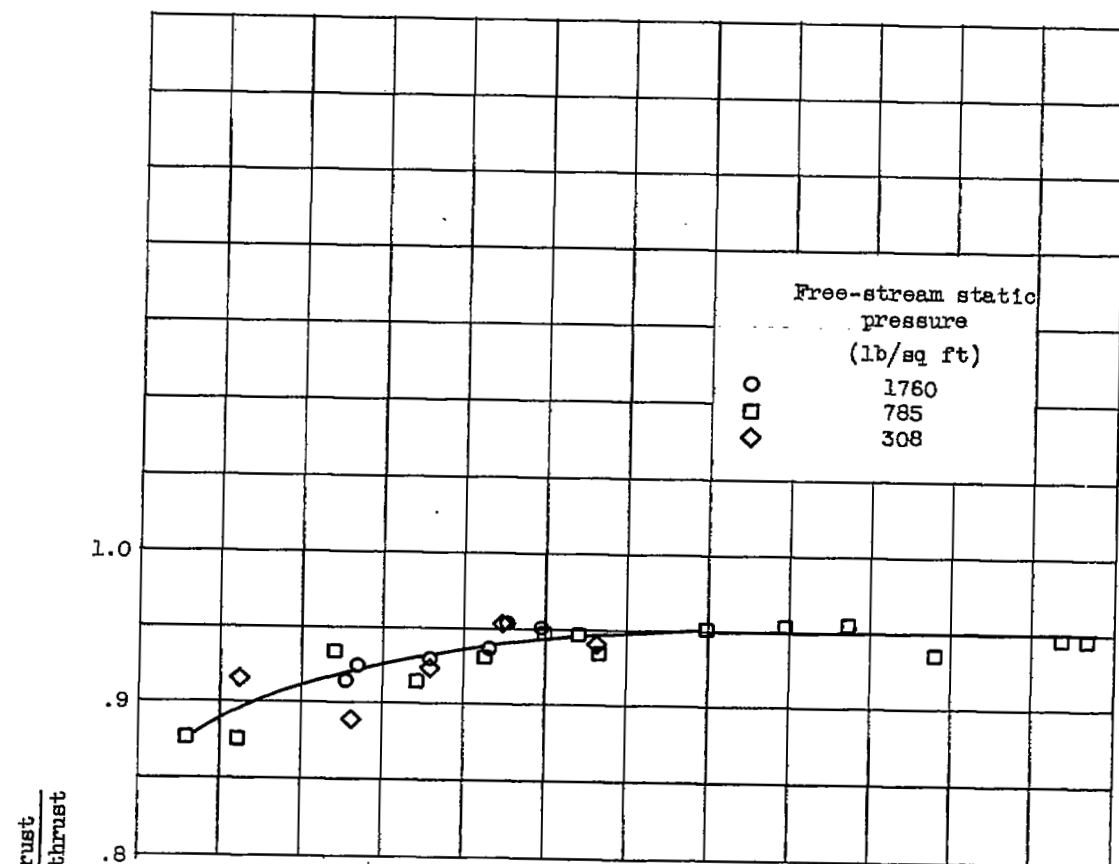
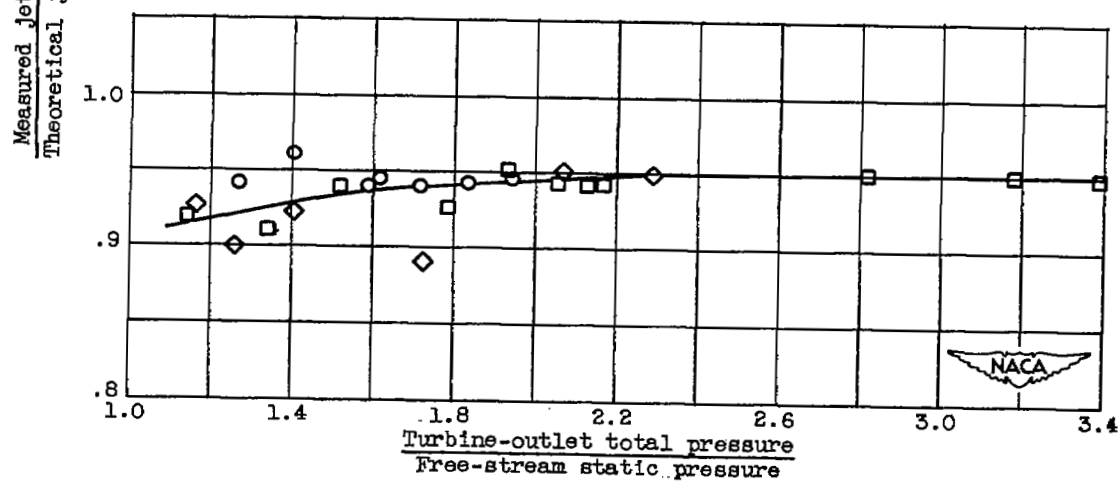


Figure 16. - Variation of combustor total-pressure-loss ratio with engine-inlet total pressure at constant corrected engine speeds for engines having tubular and annular combustors.



(a) Engine A, axial-flow engine.



(b) Engine C, axial-flow engine.

Figure 17. - Effect of altitude pressure on tail-pipe losses.

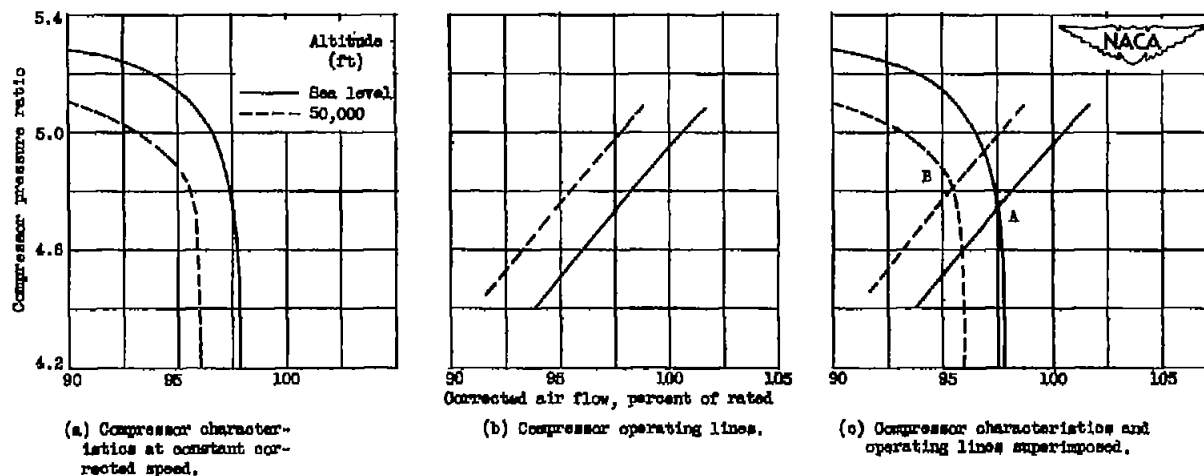


Figure 18. - Effect of altitude on compressor operating points. Engine B; axial-flow engine.

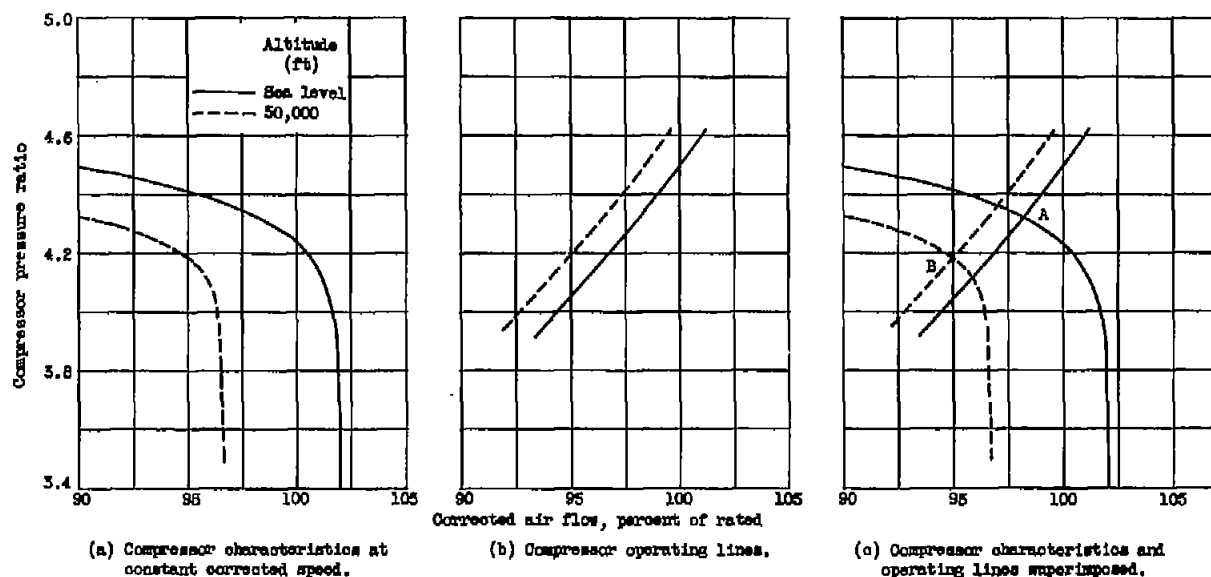


Figure 19. - Effect of altitude on compressor operating point. Engine F; centrifugal-flow engine.

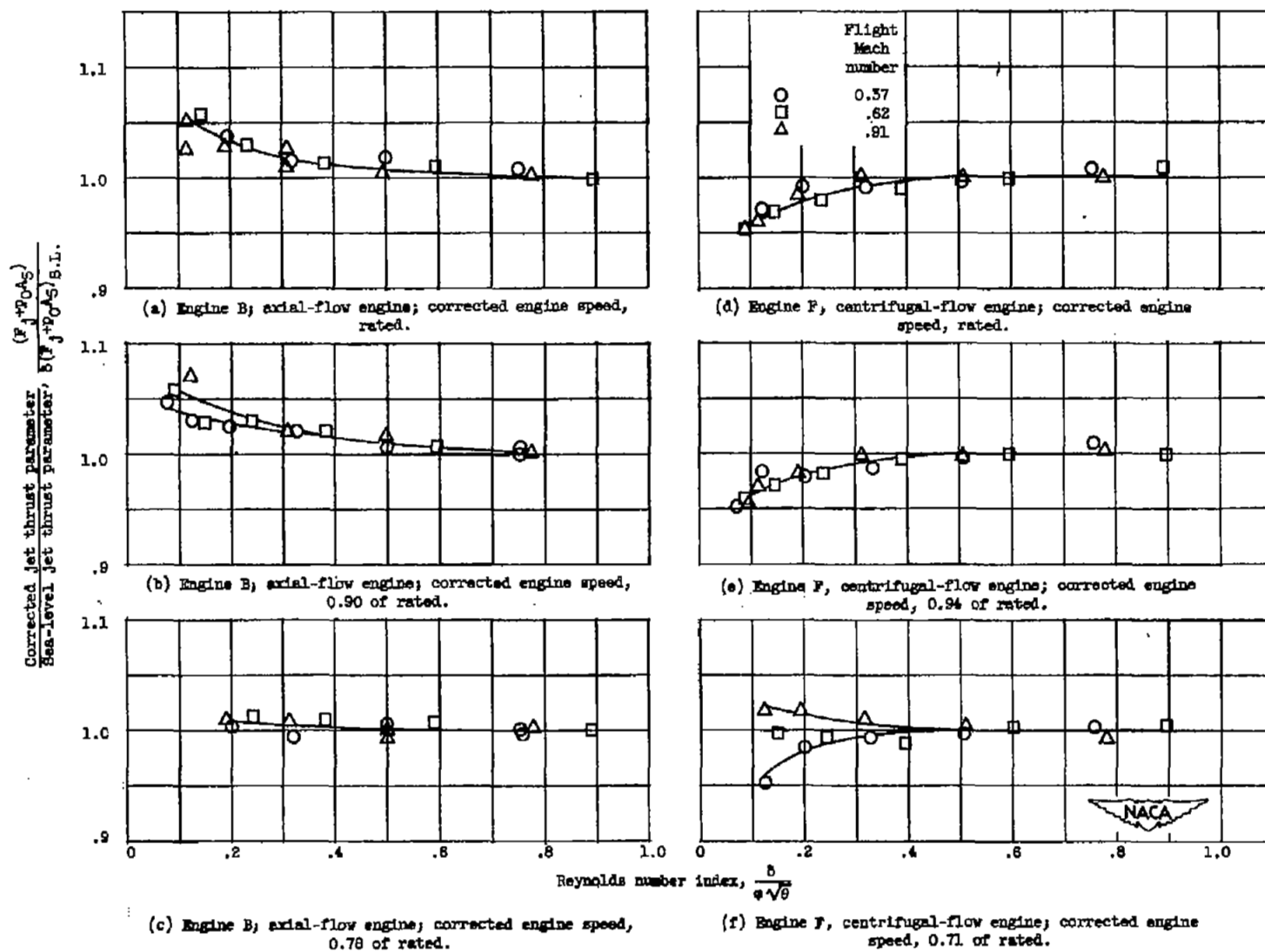


Figure 20. - Variation of actual to predicted jet thrust parameter ratio with Reynolds number index.

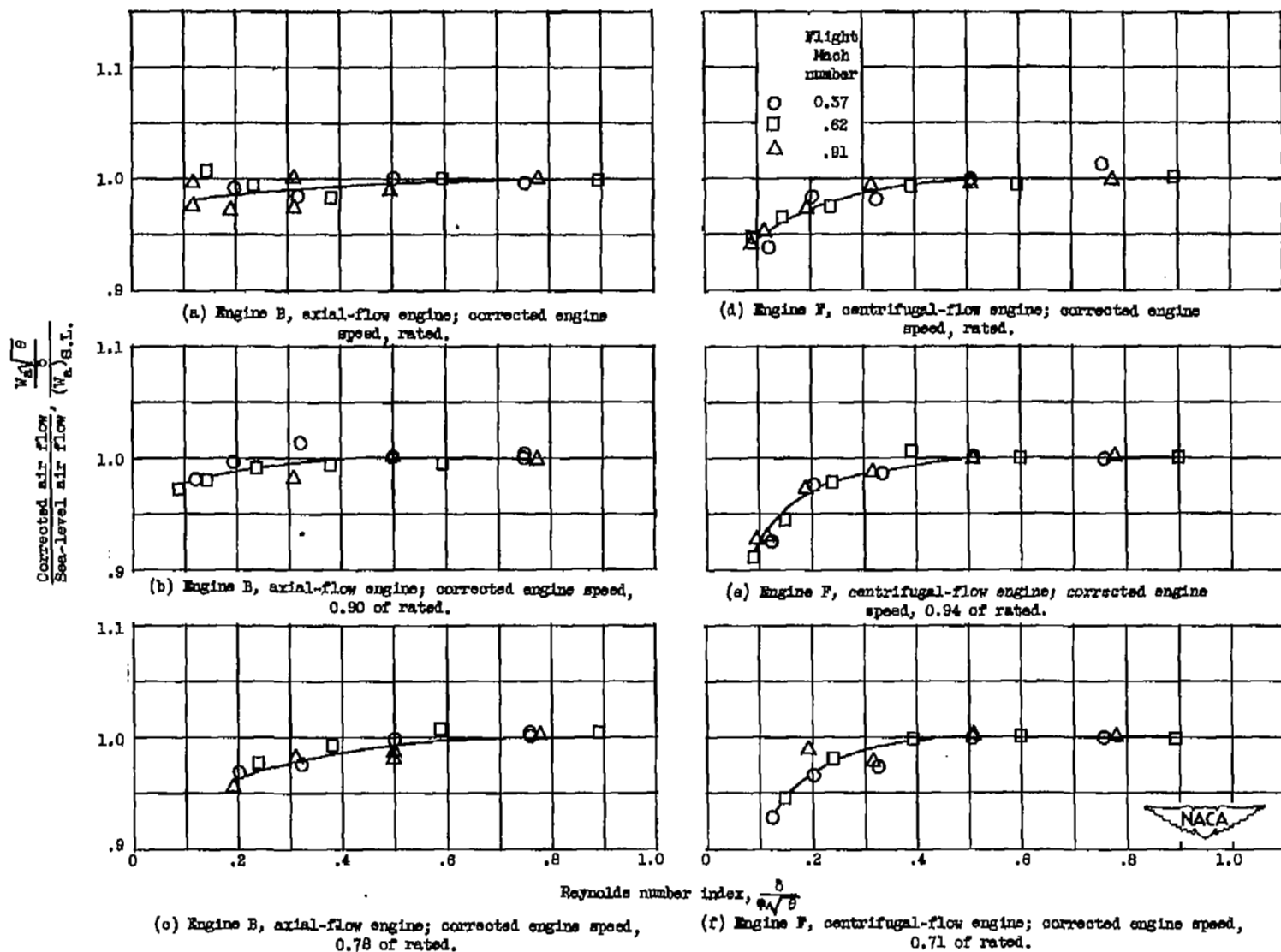


Figure 21. - Variation of actual to predicted air flow ratio with Reynolds number index.

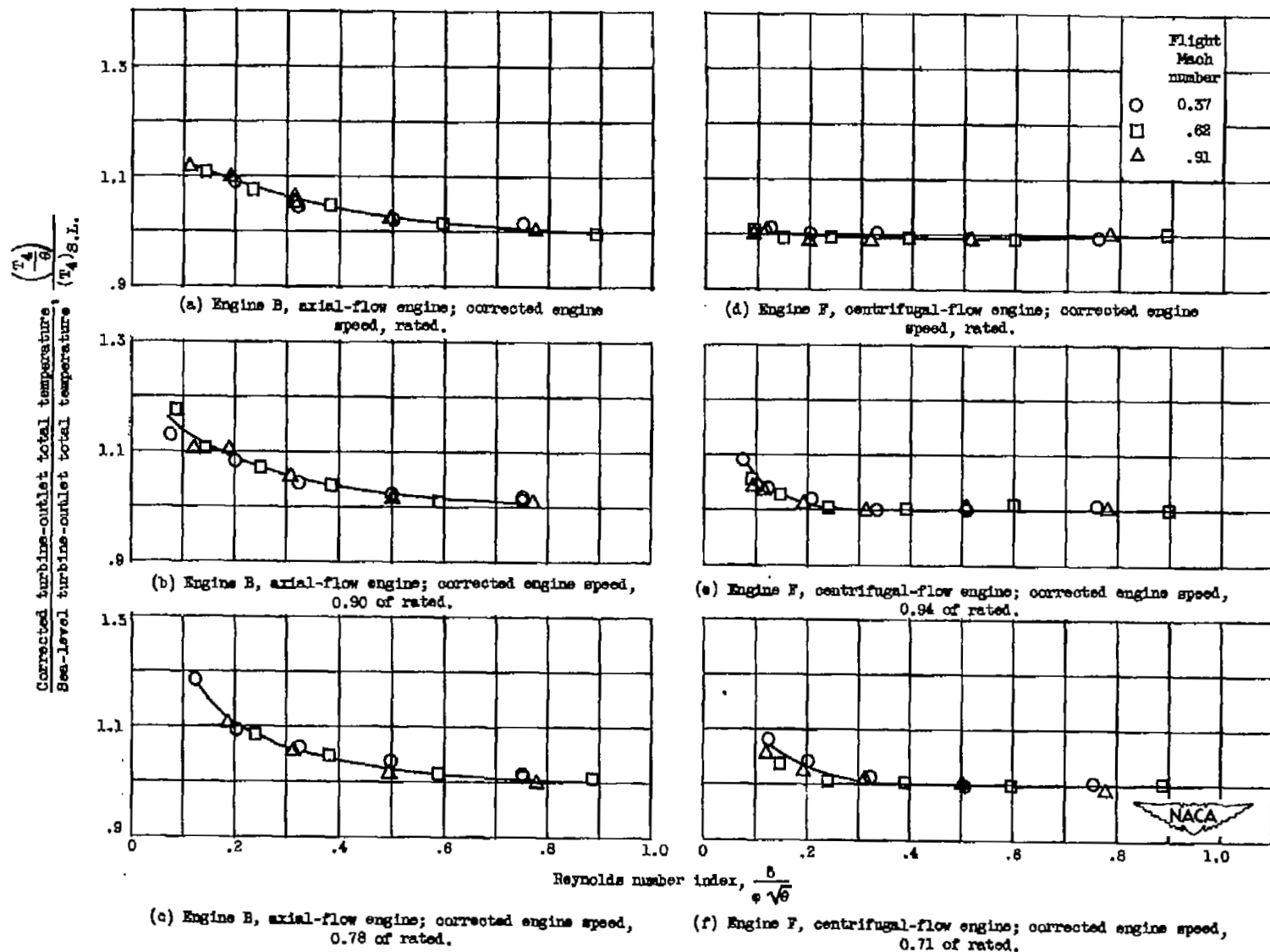


Figure 22. - Variation of actual to predicted turbine-outlet total temperature ratio with Reynolds number index.

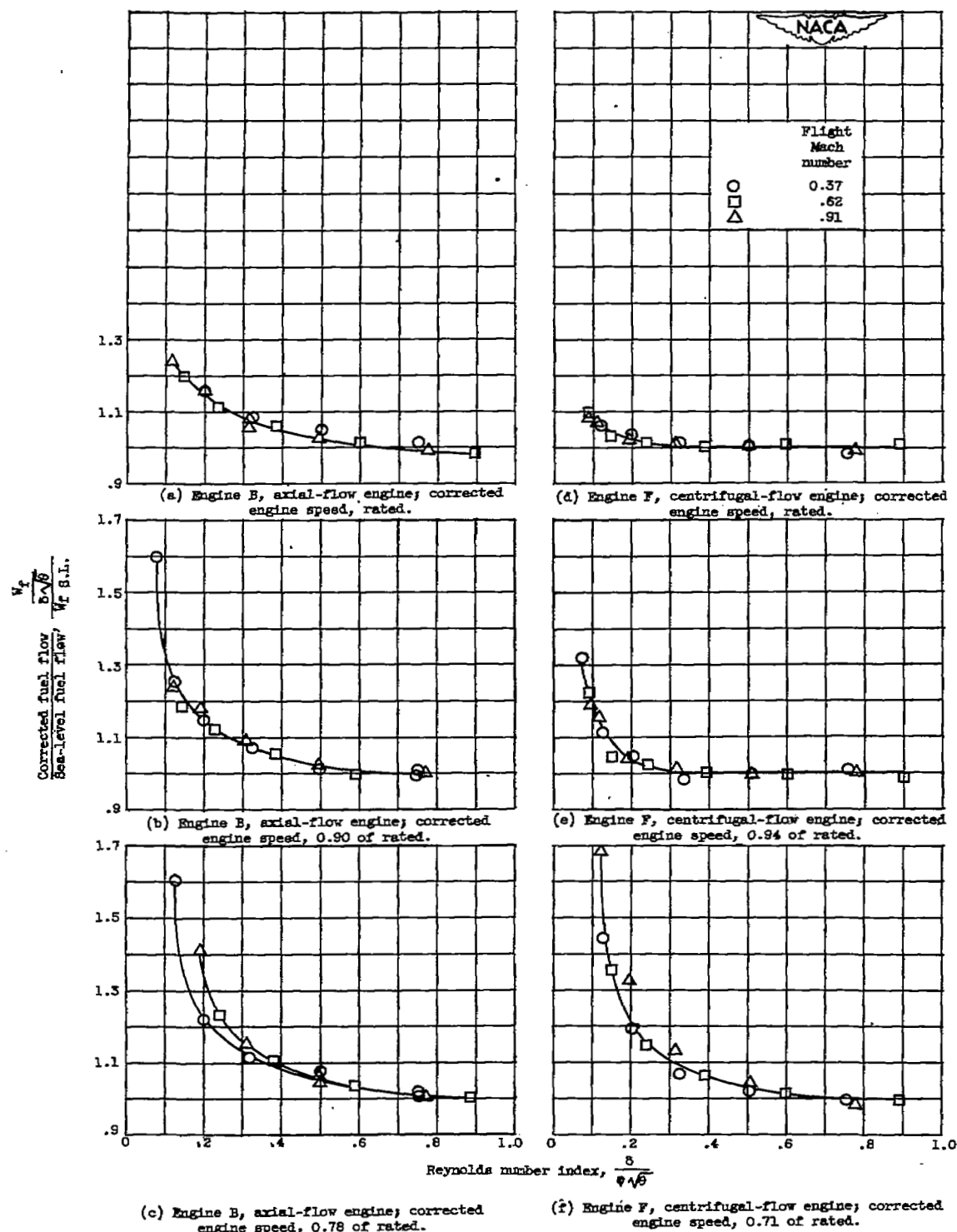
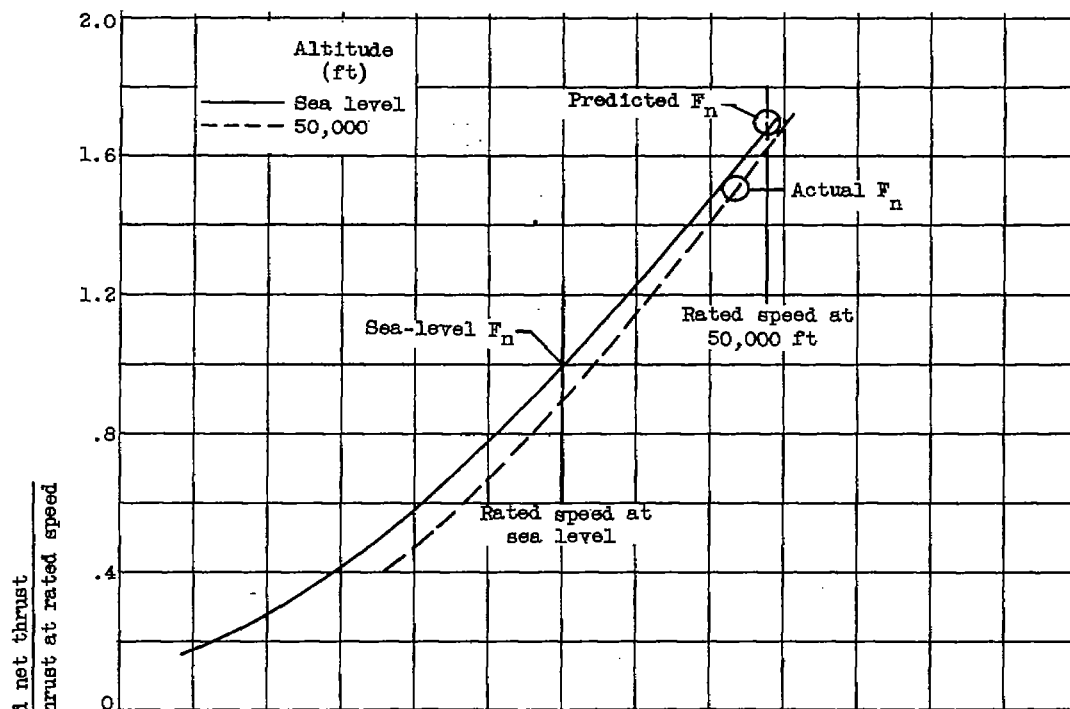
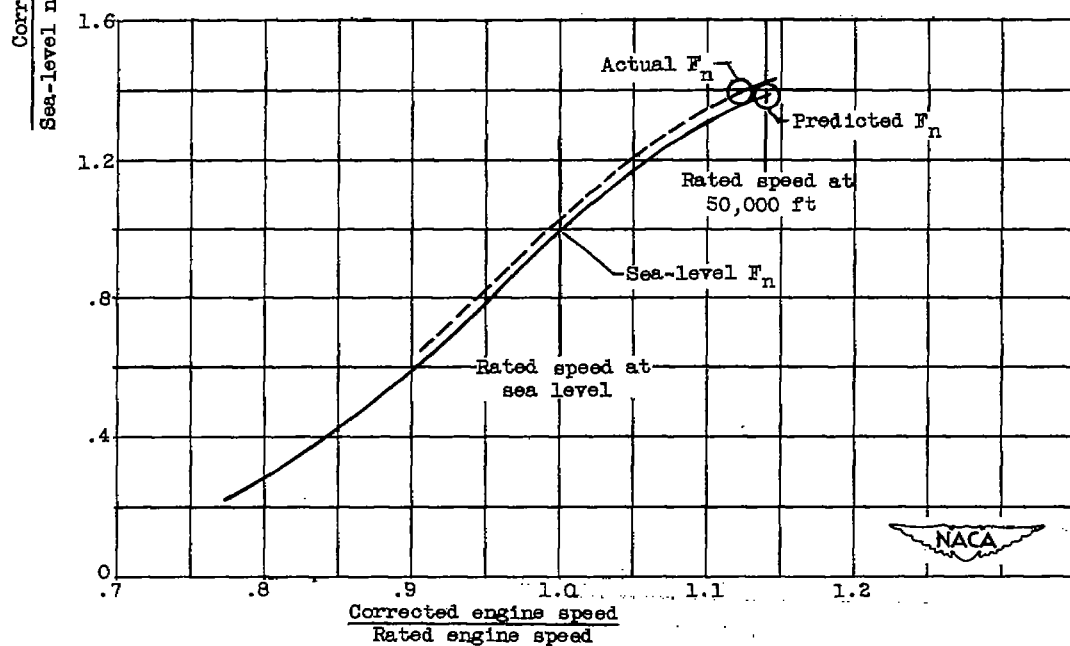


Figure 23. - Variation of actual to predicted fuel flow ratio with Reynolds number index.

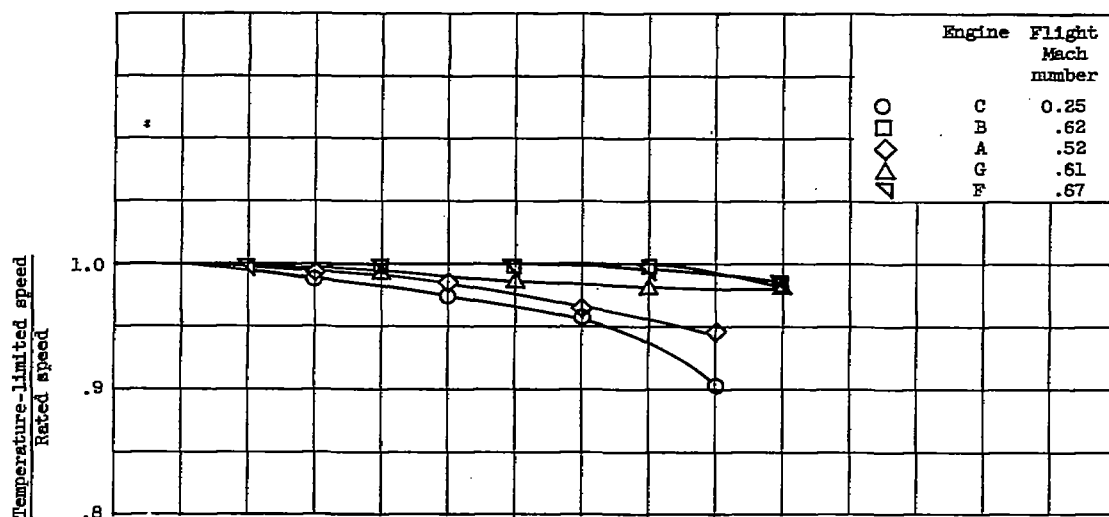


(a) Engine F, centrifugal-flow engine.

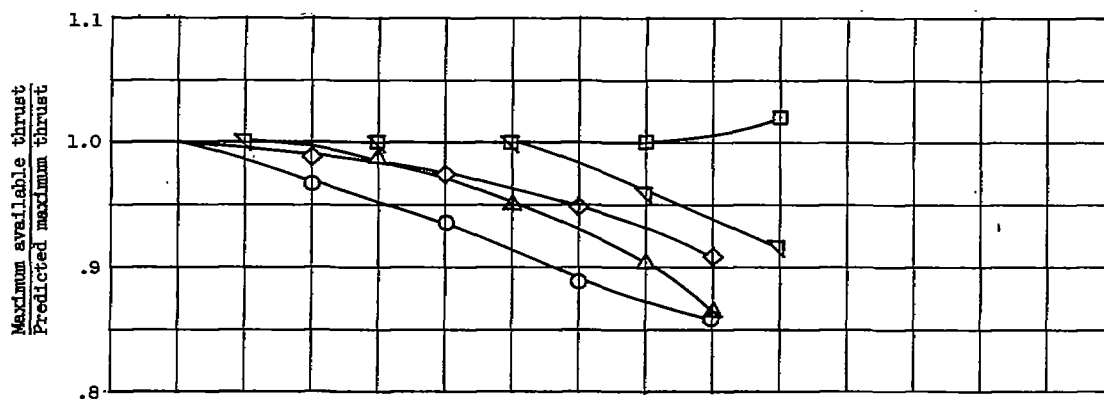


(b) Engine B, axial-flow engine.

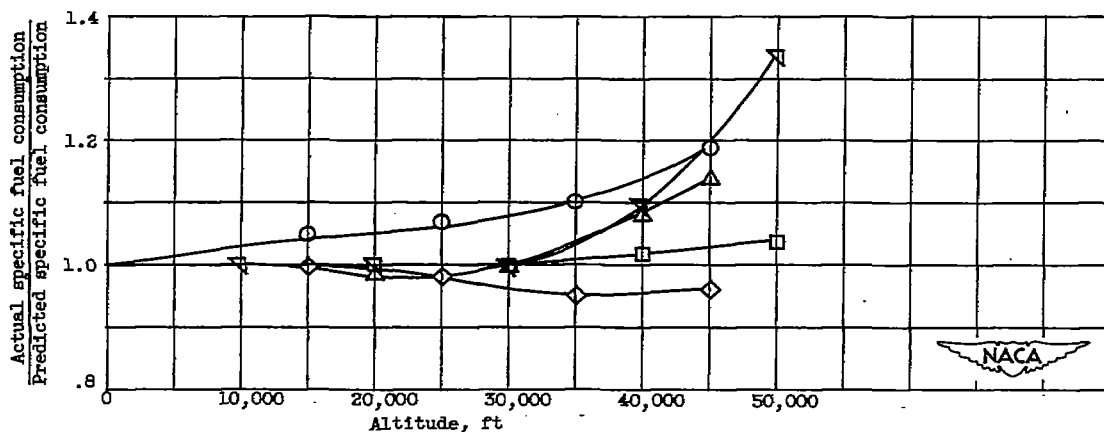
Figure 24. - Variation of corrected net thrust with corrected engine speed at two altitudes.



(a) Ratio of temperature-limited speed to rated speed.



(b) Ratio of maximum thrust to predicted maximum thrust.



(c) Ratio of actual to predicted specific fuel consumption.

Figure 25. - Variation of actual to predicted performance ratios with altitude for several axial- and centrifugal-flow turbojet engines.

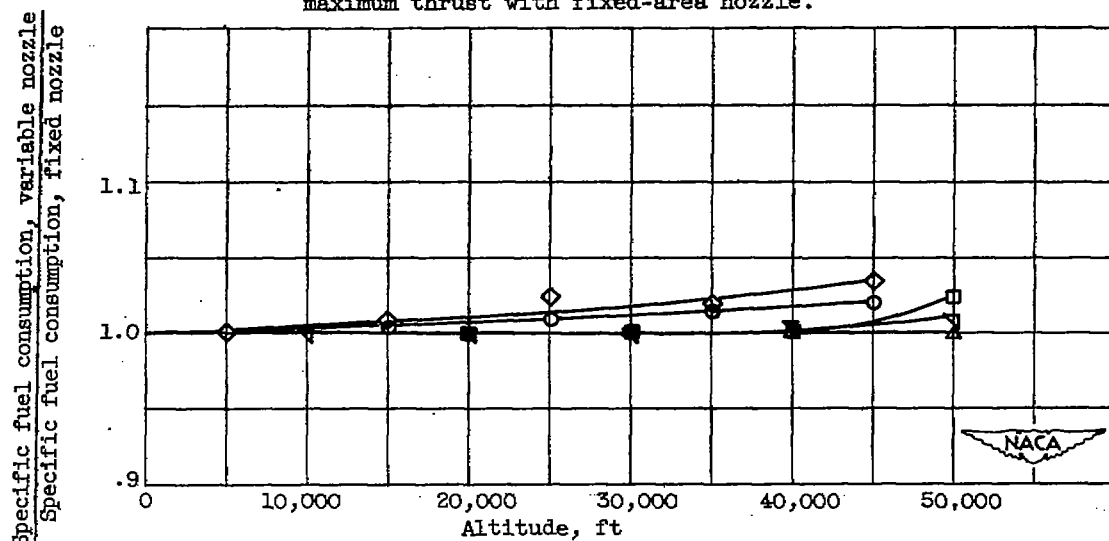
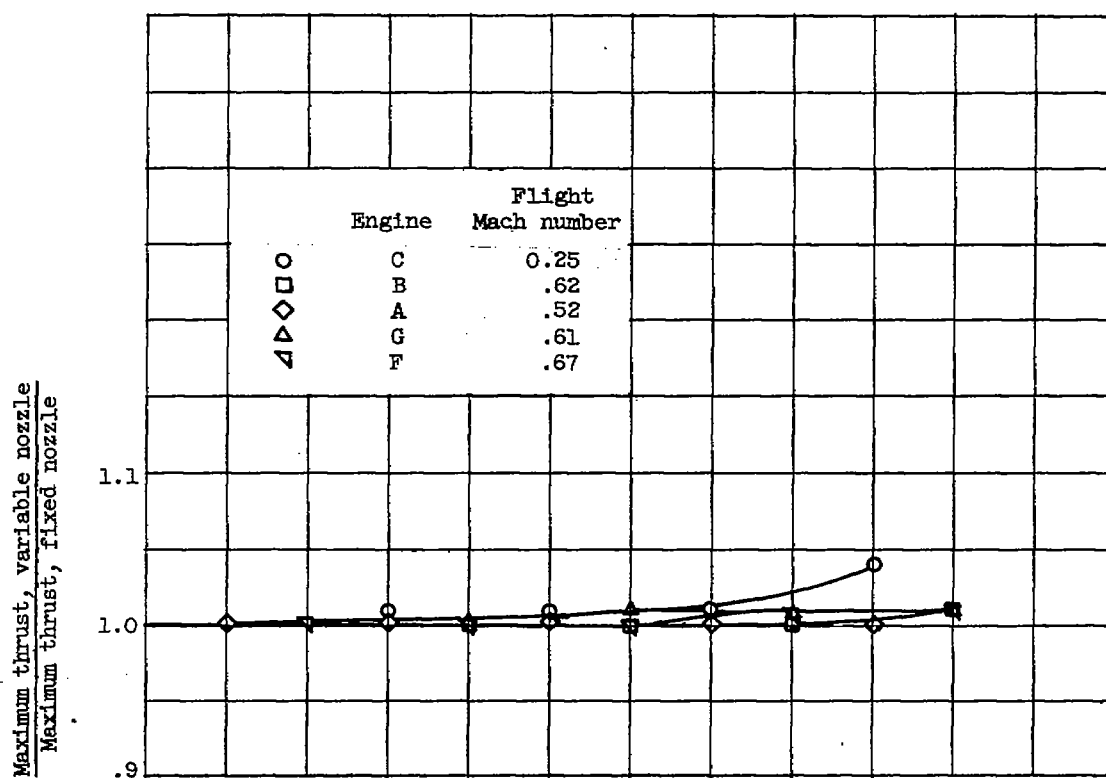
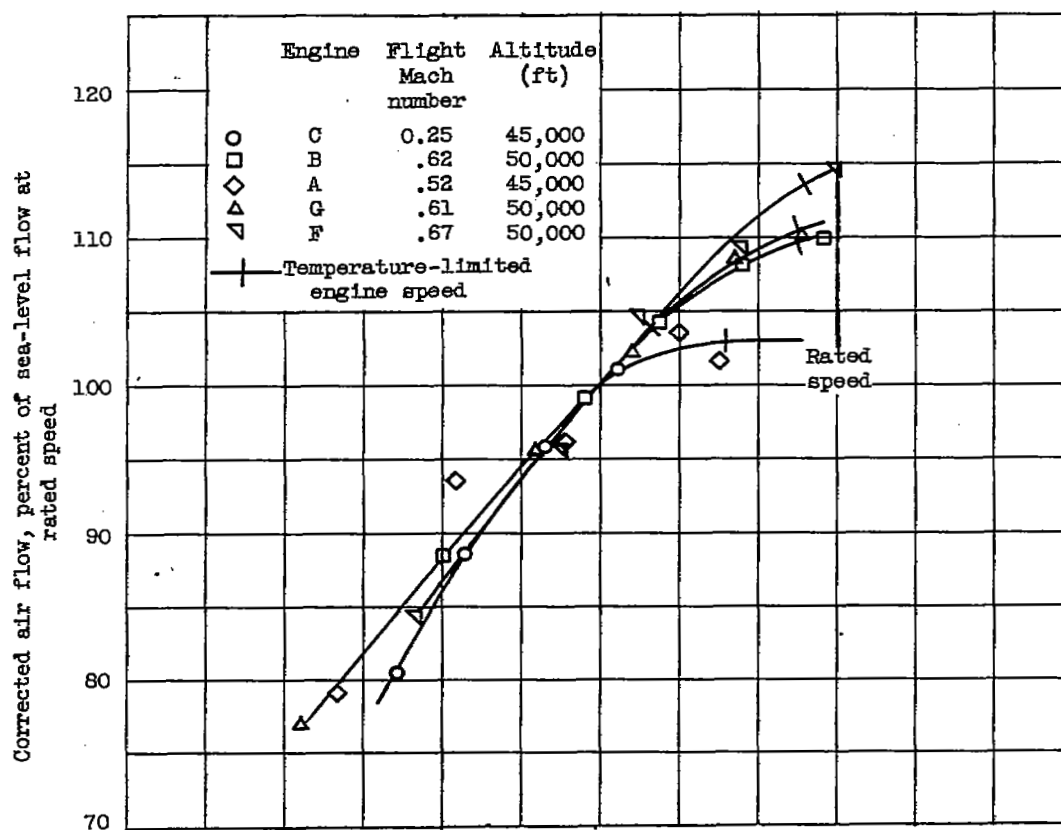
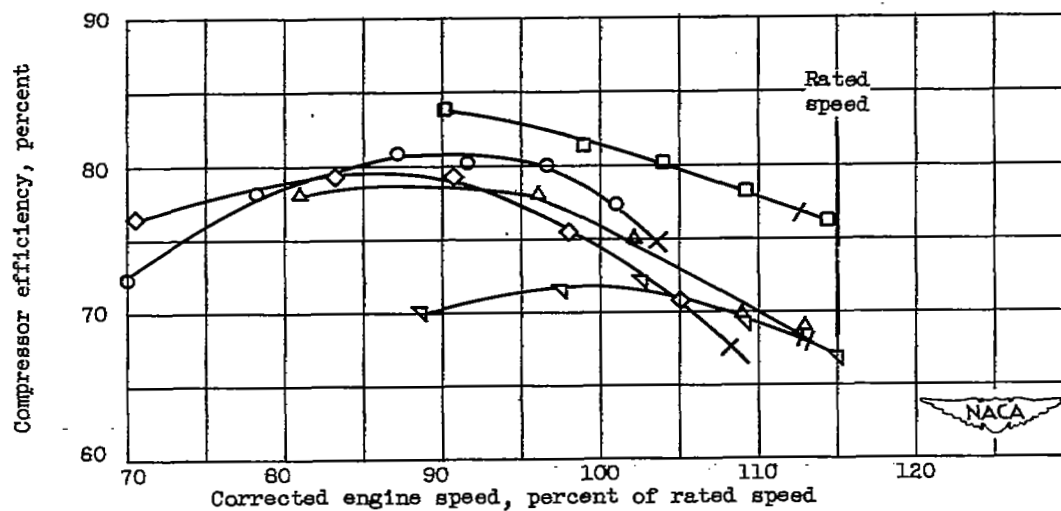


Figure 26. - Variation of variable-area nozzle to fixed-area nozzle performance ratios with altitude for several axial- and centrifugal-flow turbojet engines.

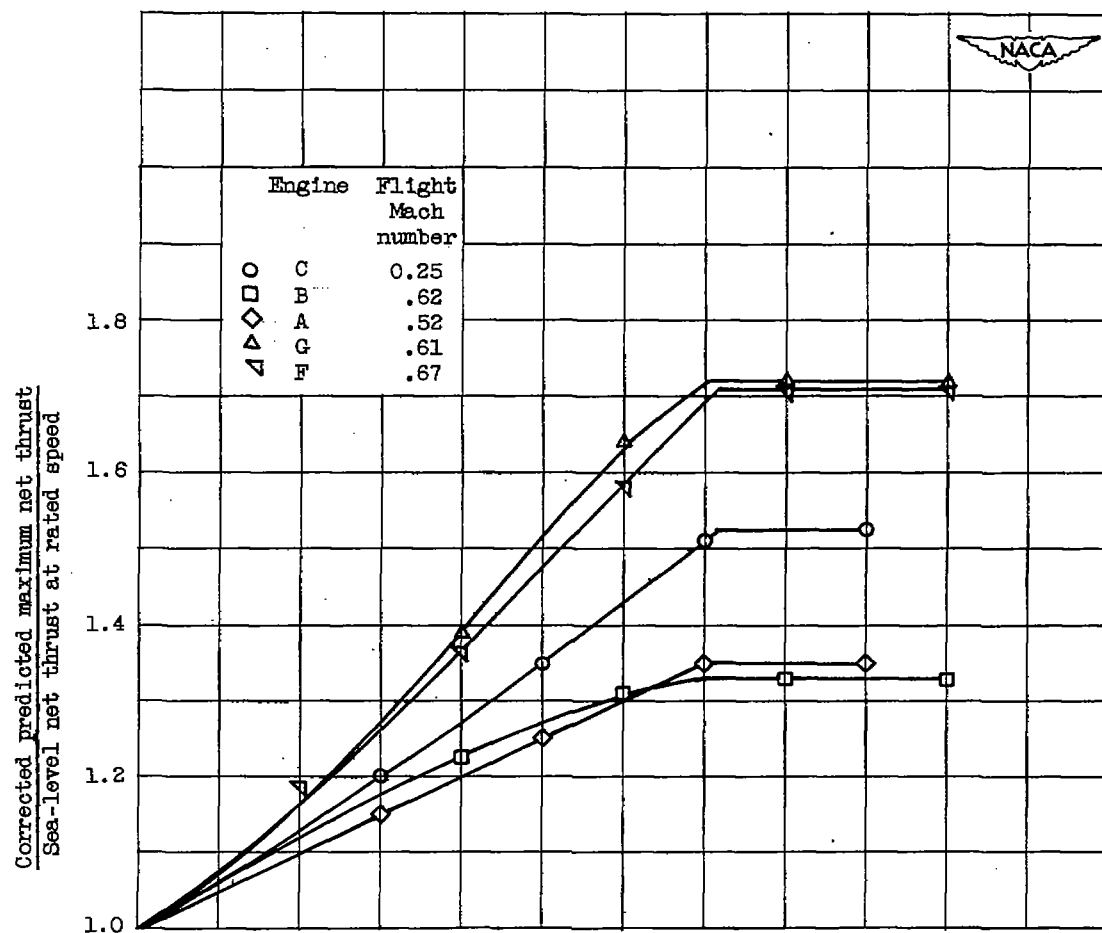


(a) Corrected air flow.

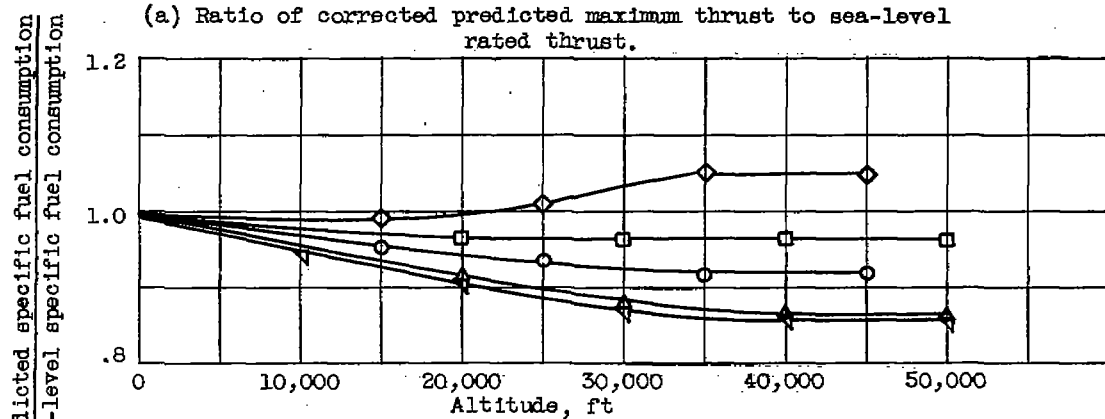


(b) Compressor efficiency.

Figure 27. - Comparison of air flow and compressor efficiency characteristics for several engines.

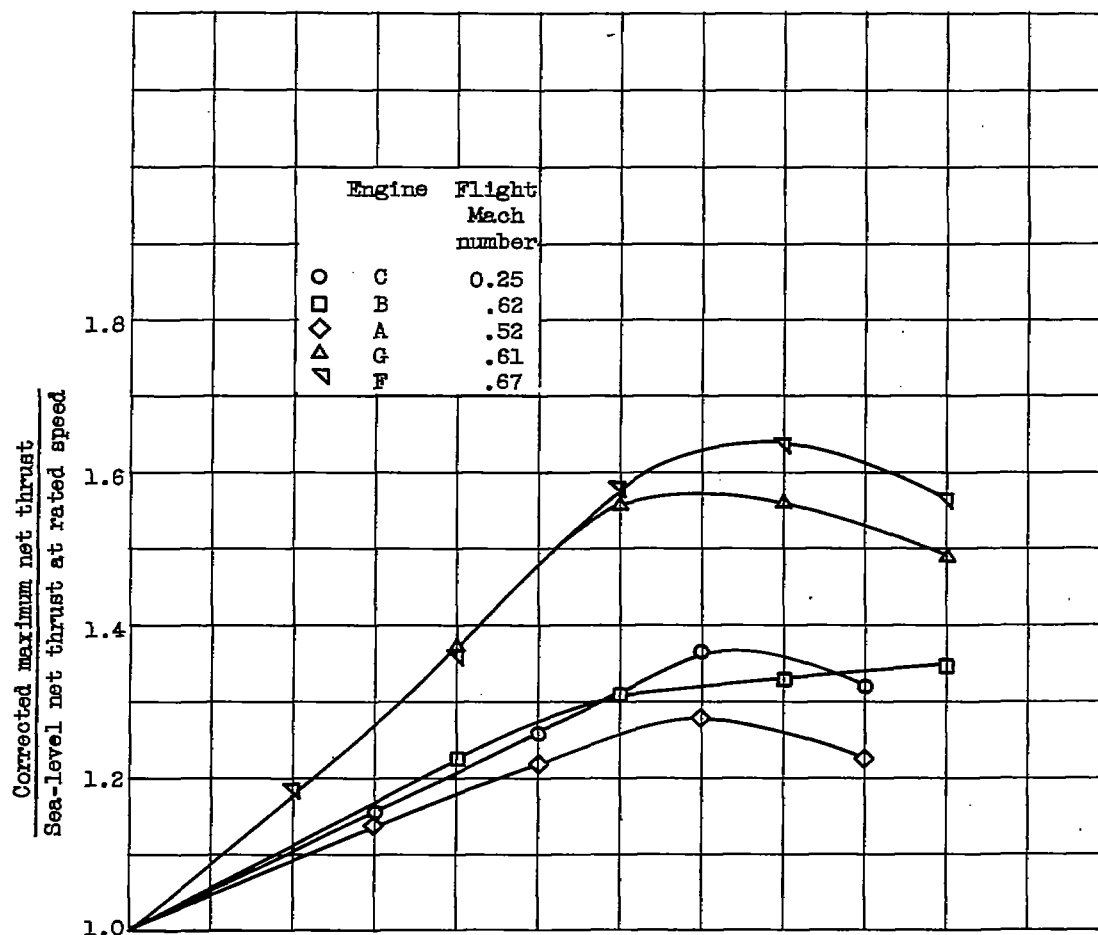


(a) Ratio of corrected predicted maximum thrust to sea-level rated thrust.

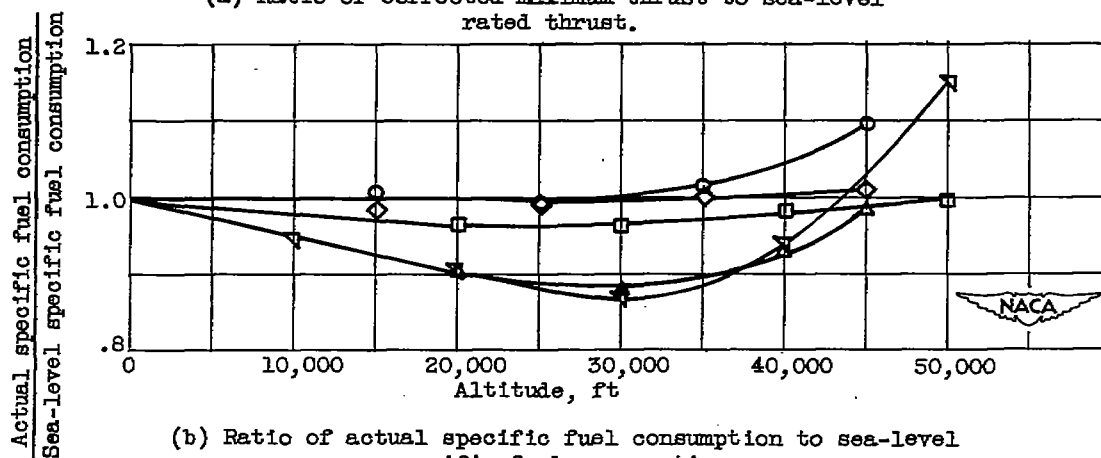


(b) Ratio of predicted specific fuel consumption to sea-level specific fuel consumption.

Figure 28. - Variation of predicted to sea-level performance ratios with altitude for several axial- and centrifugal-flow turbojet engines.

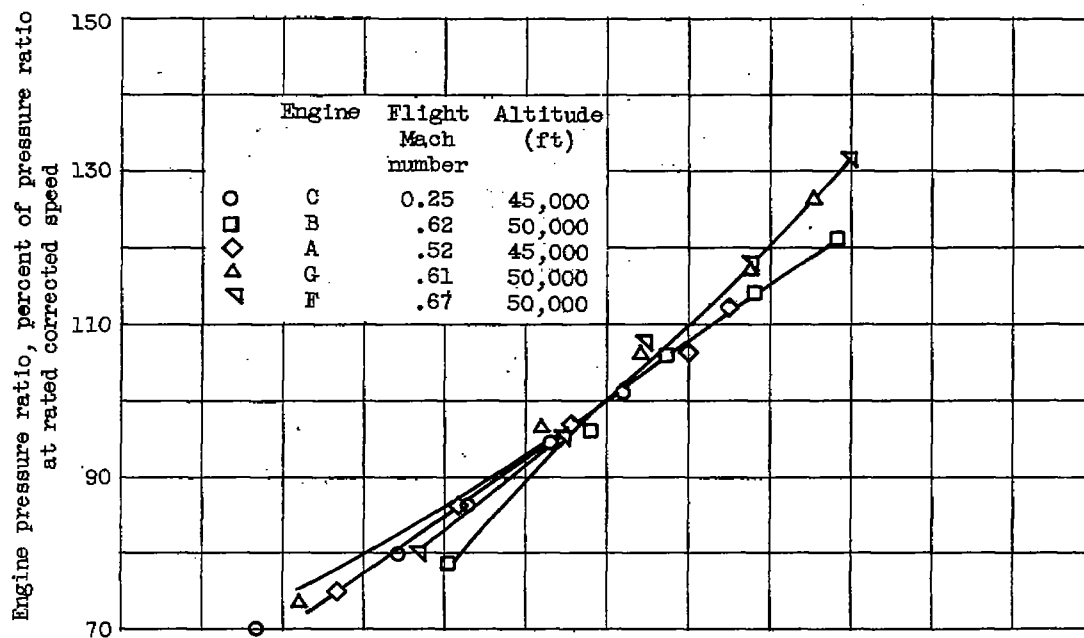


(a) Ratio of corrected maximum thrust to sea-level rated thrust.

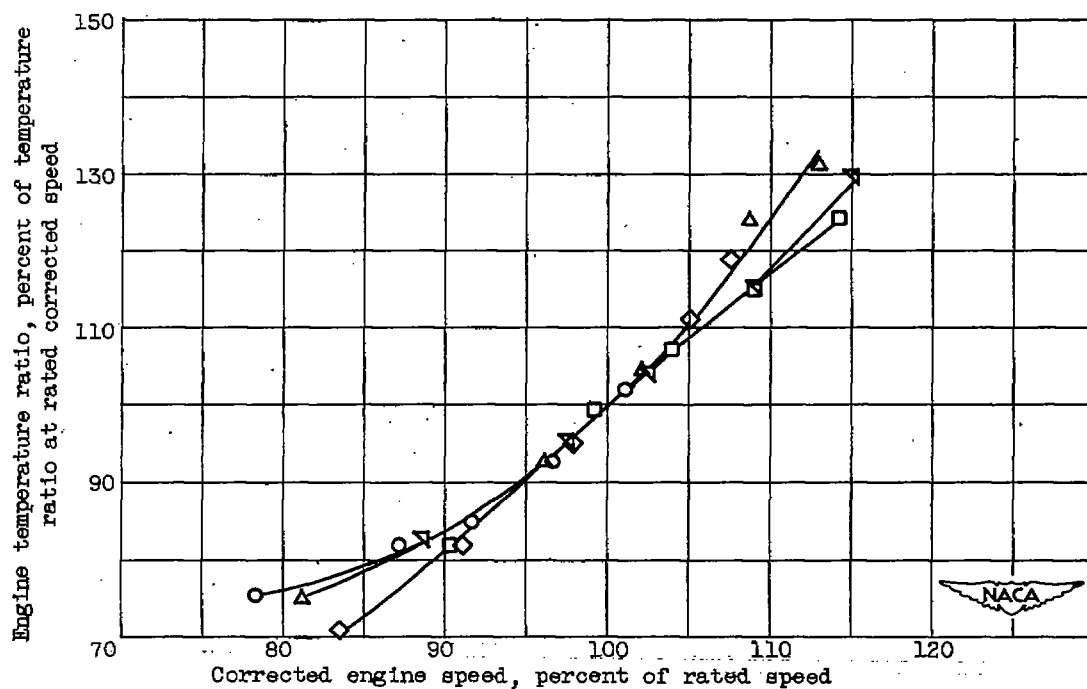


(b) Ratio of actual specific fuel consumption to sea-level specific fuel consumption.

Figure 29. - Variation of actual to sea-level performance ratios with altitude for several axial- and centrifugal-flow turbojet engines.



(a) Engine pressure ratio.



(b) Engine temperature ratio.

Figure 30. - Variation of engine pressure ratio and temperature ratio with corrected engine speed for several axial- and centrifugal-flow engines.

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